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MICROALGAE BASED PHYCOREMEDIATION OF DAIRY WASTEWATER FOR CIRCULAR BIOECONOMY: OPPORTUNITIES, CHALLENGES AND IMPLEMENTATION STRATEGIES

Running Title: Microalgal Phycoremediation of Dairy Wastewater

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Abstract

India is the world's largest milk producer (≈239.3 million tonnes per year (2023-24 and its fast-growing milk industry produces an estimated 275 million litres of high-strength wastewater each day with high nutrients and residual fats. Oleaginous microalgae such as *Chlorella, Scenedesmus, Spirulina and Desmodesmus* have been found to be a biologically sound, low carbon and resource-recovering alternative as they are able to incorporate N, P and CO_2 from dairy effluent and accumulate triacylglycerols which can be trans-esterified to biodiesel (FAME). It is seen that under tropical conditions, the Indian-isolated strains can remove >90% of the nutrients and can contain 30–50% lipids resulting in biodiesel yield of 250–360 L/ton biomass. This review i) specifically targets the unique requirements of India's dairy industry; ii) proposes a decentralized biorefinery configuration specifically aligned with GOBARdhan, SATAT and existing ETPs; iii) incorporates the techno-economic and life-cycle considerations under Indian context; and iv) provides a policy and implementation roadmap with steps that can be taken. The review concludes that if anchored in the Indian cooperative infrastructure and policy framework, microalgal biorefineries can be able to transform the dairies effluent from an environmental liability to clean water, renewable fuel, soil amendment and rural livelihood.

INTRODUCTION

The large-scale expansion of the dairy industry, particularly in the fast-growing industrialized countries like India have led to vast amount of micronutrients and macrominerals rich milk-processing wastewater (Biswas et al., 2021). The dairy industry is one of the largest global food sectors which consumes 2.5 to 4 litres of water per liter of milk processed, generates 160 million tonnes of milk per year, and generates huge quantities of wastewater, measuring 275 million litres of wastewater per day (MLD) (Leena et al., 2016). The wastewater generally contains high levels of organic and inorganic matter, nitrogen and phosphorous as nutrient, total suspended solids (TSS) and residue of fats (Hajri et al., 2024; Sinha et al., 2018). Such untreated or partially treated wastewater when discharged in natural water bodies, significantly reduce the dissolved oxygen levels, and increase eutrophication (Ravishankar et al., 2019; Fazal et al., 2021). This problem is further exacerbated as overall pollution potential increased as high strength and low strength waste streams are often not separated by the dairy plants. This has made it even more challenging for both urban and rural wastewater treatment systems (Kumari et al., 2020; Verma et al., 2022). India's importance in this context has grown even more in the latest statistical periodicity. The Department of Animal Husbandry and Dairying (DAHD, 2024) reported that milk production in India increased from 146.3 million tonnes in 2014-15 to 239.3 million tonnes in 2023-24, a 63.6% increase over 10 years, and an average of 471 g/day per capita. The USDA FAS (2024) also forecasts a production of 216.5 million tonnes milk for calendar year 2025. With the estimated water use intensity of 2.5–10 L of wastewater per L of milk processed (Chokshi, 2018; Agrawal and Sarode, 2021; Sam, 2025), the organised processing sector in the country generates conservatively 275–600 MLD of dairy effluent, mostly from the dairy clusters of Gujarat, Maharashtra, Punjab, Uttar Pradesh, Rajasthan, Karnataka and Tamil Nadu. Such massive pollution responsibilities are clearly evident in instances like the Buddha Dariya/Buddha Nullah in Ludhiana, where clusters of dairy farms pollute water bodies by releasing effluent and dung in amounts that exceed municipal STPs' design capacity (Bhardwaj, 2025). Various conventional treatment processes, such as activated sludge, advanced oxidation processes, aerobic lagoon and anaerobic digestion (which require a massive amount of space, energy and time), are used to treat dairy wastewater (DWW) (Bandara et al., 2025). While these systems can partially decrease BOD and COD, they can be less effective in the reduction of ammonia, nitrates and phosphates. Further, they require high energy consumption to operate, frequent addition of chemicals and highly skilled workers, making them economically unviable and technically difficult for the rural dairy units or plants (Chokshi et al., 2016; Shah et al., 2021). The weaknesses of these conventional systems as well as the rising global focus on resource recovery and energy-efficient waste management strategies, led researchers to look at a different way of achieving both reduction in environmental pollution and value generation from waste (Sengupta et al., 2023). Integration of biological treatment systems with the principles of circular economy is an area of interest in this context. Wastewater and effluents can be treated by a sustainable approach, and phycoremediation, by using microalgae, is one of the most interesting ways in this aspect (Rana and Prajapati 2021).

The microalgal-phycoremediation–biodiesel nexus has recently been reviewed mainly as a global, mechanism-oriented synthesis and comprehensive mapping of the science but none of them includes a country-specific operationalisation framework for India where the dairy sector is characterised by cooperatives and Small and Medium Enterprises (SME) clusters, where municipal STPs are systematically overloaded and where renewable-energy policy instruments (GOBARdhan, SATAT, PM-KUSUM, Bio-E3) provide an unusually favourable enabling environment. The present review focuses explicitly on; i) Indian dairy realities (volumes, characteristic loads, ETP gaps, climatic windows); ii) introduction of a dedicated section on techno-economic and life-cycle approach with clear linkage to Indian capital and operating cost structure; iii) presenting a decentralised, modular biorefinery configuration suitable for cooperatives and rural SMEs; and iv) presenting a stepwise policy and implementation roadmap with explicit linkage to GOBARdhan, carbon-credit registries and India's National Bio-Energy Mission.

PHYSICOCHEMICAL CHARACTERISTICS OF DAIRY WASTEWATER IN INDIA

Dairy wastewater, a by-product resulting from milk processing activities, has a highly complex composition due to the diverse operations involved in dairy plants including milk reception, pasteurization, cheese and curd production, and cleaning of equipment and pipelines (Anitha et al., 2025). These processes contribute to a heterogeneous mixture of organic and inorganic pollutants that define the physicochemical profile of the effluent (Boguniewicz-Zablocka et al., 2017). As shown in table 1, these effluents include most critical and highly fluctuating parameters such as total nitrogen (TN), total phosphorus (TP), (BOD), pH, total suspended solids (TSS), total dissolved solids (TDS), (COD), electrical conductivity (EC), and concentrations of fats, oils, and grease, presenting serious environmental challenges (Slavov, 2016). These values are really enormous when compared to municipal wastewater which indicates that the use of particular treatment systems is capable of managing such high levels of pollution burdens is required. In connection with the nature of processing activity and cleaning activities, two crucial nutrients that are enriched and essential are nitrogen and phosphorus which possess dairy effluents in good amounts such that the total nitrogen usually exceeds 100 mg/L and the total phosphorous usually exceeds 20 mg/L (Qin et al., 2016). Discharge of these nutrients into natural water bodies without adequate treatment promotes bacterial growth, algal blooms and subsequent eutrophication, leading to the depletion of dissolved oxygen and severely reduce aquatic biodiversity which leads to severe environmental issues (Abrane et al., 2021; Kookal et al., 2022). In addition, TDS in dairy wastewater, typically exceed 10-23000 mg/L (Ankoliya et al., 2022) primarily made up of casein particles, fat globules, and colloidal matter. High level of TSS hinder sunlight penetration in aquatic ecosystems and can disrupt benthic or bottom dwelling habitats when discharged untreated (Sharma et al., 2022). The pH of dairy wastewater that usually have a range of 6.0 to 10.0, determined by the cleaning agents employed and the buffering capacity of the milk-based constituents. Such changes in pH do not only influence microbial ecology of biological treatment systems used traditionally, but can also influence enzymatic processes in downstream biodiesel processing (Kumar et al., 2020). Salinity level which is a measure of wastewater's ionic content is usually indicated by Electrical conductivity (EC), which typically between 1.5 and 4.0 mS/cm. High to moderate level of electrical conductivity can poses difficulties in survival of certain freshwater algal strains, though some microalgae have demonstrated adaptive tolerance to these conditions (Kiran and Mohan, 2021). Oils and grease are also present and often contain a concentration of 100 to 500 mg/L, which leads to the organic load and can result in the formation of scum layers in open channels, hindering aerobic processes. Alternatively, when utilized in the right manner, these lipophilic substances may serve as an extra food source to lipid-accumulating microalgae, thus contributing to the synthesis of biodiesel precursors (Muthukumaran and Rajan, 2024). The nutrients and abundance of easily

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bioavailable carbon in dairy effluents under favorable conditions make them good growth media in oleaginous microalgae. Strains as *Chlorella vulgaris* and *Scenedesmus obliquus* have demonstrated increased biomass productivity and nutrient uptake when grown in such effluents, which underscores the compatibility of the physicochemical profile of the effluents and the needs of algae to develop sustainable phycoremediation systems (Talha et al., 2025).

These physicochemical parameters are essential to design the most effective phycoremediation strategies, the kinetics of algal growth, and the fusion of downstream biofuel conversion technologies (Devi et al., 2022; Rashd et al., 2025). Thus, the initial move in matching wastewater treatment with renewable energy production by means of microalgal biotechnological interventions is attentive characterization of the effluent. The dairy industries in India generate wastewater that is extremely pollutant-containing as it includes organic resources (lactose, proteins, fats), suspended solids, and residues of cleaning-chemicals. These add to high BOD and COD levels in effluents released without treatment and frequently surpassed allowed discharge standards in the environment and led to oxygen depletion in the receiving water bodies - (Courseware, 2020).

Table 1. Physicochemical characteristics of dairy wastewater in India.

Parameter	Typical Range	Significance / Characteristics	References
pH	6.0 -10.0	Influenced by cleaning agents, detergents, acidic whey discharge	Tetra pak, 2022
BOD (mg/L)	40 - 48,000	High biodegradable organic load from lactose, fats, proteins	Slavov, 2016
COD (mg/L)	2,500 - 95,000	Total oxidizable organic matter; very high in concentrated streams	Slavov, 2016
TSS (mg/L)	500 - 23,000	Casein particles, fat globules, suspended milk solids	Slavov, 2016
Total Nitrogen (mg/L)	80 - 150+	Derived from milk proteins and ammonia residues	Leistner, 2025
Ammoniacal Nitrogen (mg/L)	20 - 120	Easily assimilable nitrogen source for microalgae	Leistner, 2025
Total Phosphorus (mg/L)	15 - 50	From milk constituents and phosphate detergents	Leistner, 2025
Orthophosphate (mg/L)	10 - 40	Bioavailable phosphorus fraction	Leistner, 2025
Oil and Grease (mg/L)	100 - 500	High in butter/cream production units	Leistner, 2025
Turbidity (NTU)	100 - 400	Due to colloidal fats and proteins	Al-Qodah et al., 2024

Electrical Conductivity (mS/cm)	1.5 - 4.0	Indicates salinity; affects algal strain tolerance	Al-Qodah et al., 2024
Total Dissolved Solids (mg/L)	1,000 - 5,000	Dissolved salts and organic residues	Leistner, 2025
Dissolved Oxygen (mg/L)	< 2 (untreated)	Rapid oxygen depletion due to high BOD	Slavov, 2016
Alkalinity (mg/L as $CaCO_3$)	200 - 800	Buffering capacity influenced by detergents	Slavov, 2016
Chlorides (mg/L)	100 - 600	From cleaning chemicals and process water	Velmurugan and Pandian, 2024
Sulphates (mg/L)	50 - 300	Cleaning agents and process additives	Velmurugan and Pandian, 2024
Lactose (mg/L)	500 - 5,000	Major organic carbon source	Leistner, 2025
Fats (mg/L)	200 - 1,000	Energy-rich but causes scum formation	Leistner, 2025
Temperature (°C)	25 - 40	Warm effluent favours microbial growth	Al-Qodah et al., 2024

Dairy Wastewater Treatment Challenges in India

The Dairy industries generate copious volume of wastewater during various different manufacturing and processing stages (Kwangdinata et al., 2014), which has a notable effect on environment (Kanekanian, 2006). However, to prevent the risk of environmental pollution, it is crucial to properly treat DWW before releasing into coastal water, rivers and lakes. In India, managing and treating dairy waste water presents a unique set of technical, environmental, and policy-related challenges that hinder the full-scale implementation of a sustainable solution (Premaratne et al., 2021; Ganta et al., 2022). Since India is among the largest dairy products producers and consumers in the world, the quantity of wastewater produced by milk processing plants, cooperative dairies, and rural clusters is ever-increasing at a startling rate (Agrawal and Sarode, 2021). This wastewater is not only voluminous but also very heterogeneous in terms of its physicochemical content with seasonal changes in dairy production, irregular feedstock and cleaning regimes (Roufou et al., 2021). Several interlinked issues exist in dairy wastewater treatment in India due to the variable nature of the dairy sector and the shortage of infrastructure. The seasonal changes directly influence treatment procedures, biological in particular (Sengupta et al., 2023). The problem of seasonal fluctuations in the characteristics of effluents is one of the most technical ones (Comber et al., 2019). Organic load in wastewater may surpass the treatment capacity of most of the conventional systems during peak production months. Conversely, low production years can result in an inadequate nutrient profile, and thus, unreliable performance. The existing processes, including centrifugation, flocculation, and membrane filtration, have high operational costs or add chemicals that complicate the subsequent steps (Nitsos et al., 2020). In rural and semi-urban Indian environments, the wastewater remediation is severely hindered by the absence of cost-effective and scalable systems (Shah et al., 2021). Another significant obstacle is the low-resource or decentralized dairy clusters which makes the effluent treatment systems logistically difficult and financially inaccessible, that is further complicated by regulatory and infrastructural factors (Passell et al., 2011; Ramsuroop et al., 2024). The situation is no less complicated on the economic and policy front. There is currently a lack of robust government incentives or financial mechanisms specifically designed to support dairy wastewater treatment technologies in India (Nguyen et al., 2022). Most small and medium dairy enterprises, which dominate the sector, are unable to bear the capital and operational expenditures associated with wastewater remediation (Dragone, 2022). Furthermore, the enforcement of water pollution standards is not uniform in India, although they have been provided under the under the Water (Prevention and Control of Pollution) Act (Thatai et al., 2018; Basu Roy, 2019). Most dairies in the country discharge effluents either untreated or partially treated into water bodies mainly because of poor policing and enforcement, limited technical expertise, or absence of affordable alternatives (Sengupta et al., 2023).On the policy enforcement side, the Water (Prevention and Control of Pollution) Act, 1974 and discharge norms for industries applicable for inland surface water disposal (BOD < 30 mg/L; COD < 250 mg/L; TSS < 100 mg/L) are applicable to the disposal of dairy effluent in India. Overall, the rate of compliance of small and unorganized dairies is below 50% in each CPCB and SPCB audit conducted (CPCB, 2023). The Guidance Document for Milk and Milk Products issued by the FSSAI in 2019 requires adequate ETP capacity in all licensed dairies, however rural dairies and Tier-3 town dairies (which are the majority of dairies) often have septic tanks or open lagoons. The Punjab Pollution Control Board's guidelines and guidelines of 2020 regarding the environmental management of dairy farms and gaushalas tried to tackle this issue, but there is lack of manpower and metering facilities to enforce it. This regulatory asymmetry (strong norms, weak enforcement) is the policy context for encouraging low cost, low skill biological treatment systems, such as microalgal phycoremediation, which has been found to be particularly appealing for capital-constrained SMEs.

MICROALGAE AS A PHYCOREMEDIATION AGENT

Microalgae are microorganisms that consist of a single cell, are photosynthetic, and are easily reproducible and can grow rapidly using sunlight and carbon dioxide, nutrients found in wastewater (Gupta et al., 2017; Talib et al., 2023). A very beneficial property is their capacity to efficiently uptake nitrogen, phosphorus and low levels of heavy metals from complex wastewaters. It is a low cost, low energy and carbon-neutral treatment for wastewater and produces biomass that can also be utilized as a renewable resource to generate bioenergy, thus inspiring resource recovery (Pancha et al., 2014). Microalgae based wastewater treatment which is often referred as microalgal phycoremediation is an ecofriendly and sustainable approach,

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specifically well suited in the context of dairy wastewater, is of particular interest due to composition of effluent's favorable nutrient profile for algal growth and development (Plöhn et al., 2021; Abdelfattah et al., 2022). Apart from bioenergy uses (as shown in fig 1), microalgal biomass can be used to extract high-value compounds like pigments and vitamins for animal feeds, biofertilizers, biopolymers, bioactive molecules with anti-inflammatory, antimicrobial and antitumor activity (Ma and Hu, 2023). Various chemical and thermochemical processes can be employed to convert the lipid-rich microalgal biomass into biofuels such as biodiesel, bioethanol, biohydrogen, bio-gas and bio-oil. After lipid extraction and transesterification, the produced biodiesel makes the wastewater treatment process a bioenergy production platform (Roy et al., 2025). The most significant difference between the microalgal systems and other bioremediation technologies is that they are not only able to treat raw and untreated wastewater but they also produce valuable biomass compounds such as lipids, proteins, and carbohydrates (Fal et al., 2022; Talha et al., 2025).

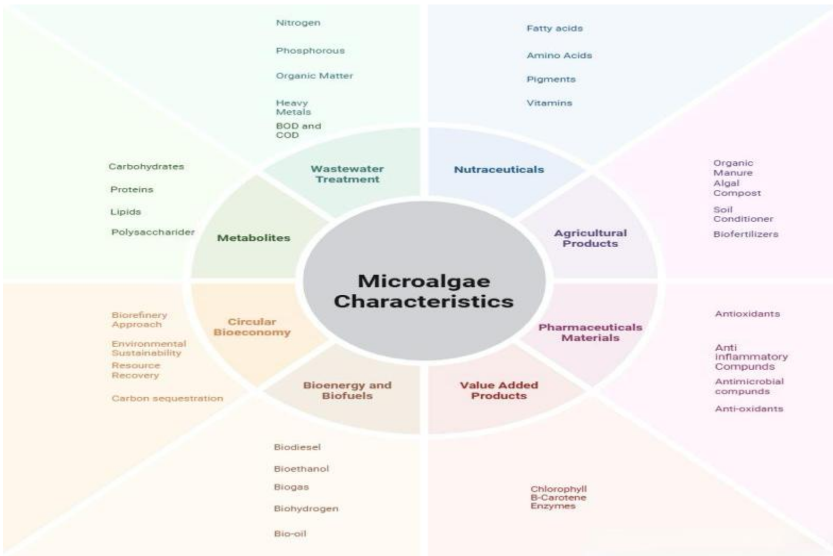

Fig. 1. Key characteristics of microalgae.

Mechanism of Phycoremediation

Microalgal phycoremediation involves a range of biological mechanisms shown in Fig. 2, through which microalgae participate in removal of pollutants and water reconditioning (Melo et al., 2022; Ooi et al., 2023). Phycoremediation is a versatile and multipurpose study, widely explored by researchers for its dual-purpose role in different wastewater treatment process and biofuel production (Singh et al., 2021; Elsayed et al., 2024). Integrating climate resilience of microalgal phycoremediation for energy recovery, and wastewater valorization makes it a promising candidate for scalable deployment in India's dairy clusters and elsewhere (Handayani et al., 2020). One of the most fundamental processes implicated is the assimilation of organic and inorganic nutrients, notably nitrogen and phosphorus which are in high concentrations in dairy wastewater. These nutrients, although problematic due to the stimulation of eutrophication on discharge into open water bodies, are essential microalgal growth factors (Ravikumar et al., 2021). Accession of the nitrogen by microalgae is in the form of ammonium, nitrite, and nitrate and is incorporated in the structure and metabolism of the cell as amino acids and proteins (Salbitani and Carfagna, 2021). Similarly, phosphorus is also absorbed as predominantly orthophosphate which are used in the production of ATP and nucleic acid (Rawat et al., 2020; Wagner, 2023). It can dramatically reduce nutrient effluent content by efficiently capturing them by algal cells, and in favorable growth conditions, it can often exceed 80 percent efficiencies (Chokshi et al., 2016; Kiran and Mohan, 2021). Microalgae have also been demonstrated to have considerable absorption and detoxification capacity of heavy metals and organic pollutants in addition to their nutrient absorption (Priya et al., 2022). Some of the processes that enable this to be achieved include biosorption, bioaccumulation, and enzymatic transformation (Abomohra et al., 2022). The negatively charged polysaccharides and proteins of the outer wall of the algal cell walls provide binding sites to receive positively charged metal ions like lead, cadmium, chromium, and zinc (Ciancia et al., 2020). These metals ions can then be sequestered intracellularly by physical and chemical adsorption or by making them less bioavailable by complexation (Kumar et al., 2024; Bhalani et al., 2022). Some strains of algae also secrete enzymes capable of breaking down organic pollutants like phenols, dyes and residual cleaning agents that are normally present at the dairy and food industry wastewater. This versatile capability of removing pollutants not only expands the application of phycoremediation but also enables the treatment of mixed industrial effluents with shifting composition (Gauje et al., 2022; Sharma et al., 2022). Microalgae utilize CO_2 and sunlight to produce biomass and oxygen during the day through the Calvin cycle, which neutralizes the effect of greenhouse gases and also generates oxygen that nourishes aerobic communities of microbes (Sun et al., 2018; Bora et al., 2024). The process is also useful in stabilizing pH in wastewater. Most industrial effluents such as dairy units have variable pH because of the alkaline wash solutions or acidic detergents (Lamichhane et al., 2017). Microalgae serve as natural buffers because they stabilize the carbonic acid equilibria and, in most cases, stabilize the pH to a neutral state due to the uptake of CO_2 and the use of bicarbonates (Saranya and Shanthakumar, 2021; Khoo et al., 2023). These mechanisms combined render phycoremediation a holistic and sustainable wastewater treatment method, which provides both pollutant removal, pH control, carbon capture, and biomass generation in a single biological platform (Kumar et al., 2024). The phycoremediation process is highly adaptable to the treatment of dairy and other strong effluents because microalgae eliminate and convert wastewater contaminants through a combination of complementary biological and physicochemical pathways (Kundu et al., 2024).

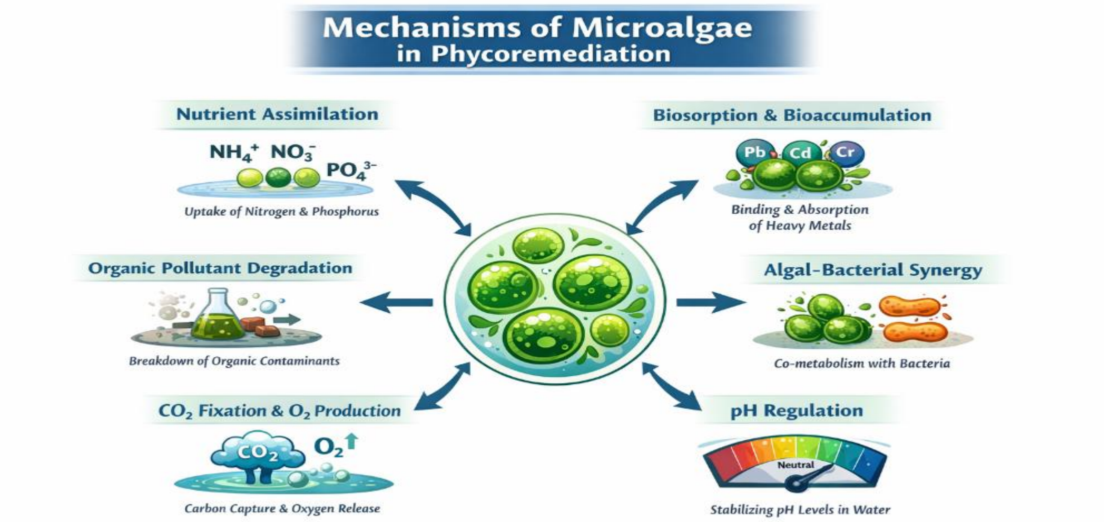

Fig. 2. Mechanisms of microalgal phycoremediation.

The key mechanisms include: (1) nutrient assimilation (uptake and incorporation into biomass), (2) biosorption and bioaccumulation of metals and charged pollutants, (3) biodegradation or transformation of organic contaminants (usually in collaboration with bacteria), and (4) ecosystem services related to photosynthesis (CO_2 fixation, O_2 release, pH buffering) that enhance downstream biological processes. Each of the mechanisms exists at varying timescales and are regulated by strain physiology and the environmental conditions (light, temperature, C source, N:P ratios) (Abdelfattah et al., 2022).

Nutrient uptake and assimilation — Microalgae can be used as the effective biological sinks of inorganic nitrogen (NH4-, NO3-, NO2-) and phosphate. Dissolved inorganic nitrogen and phosphorus are absorbed by cells and incorporated into amino acids, nucleotides and phospholipids and builds biomass under mixotrophic or heterotrophic conditions may also assimilate some organic N/C directly (Ahmad and Ashraf, 2024). During continuous or batch growth, the rate of nutrient loss tends to follow a pattern with the biomass productivity and hence the environment that supports growth (sufficient light, CO_2, moderate organic load) results in a rapid loss in N and P. One of the most popular methods to optimize both the pollutant removal and downstream lipid accumulation is through manipulation of the cultivation regime (e.g., a nutrient-saturated growth phase and nutrient limitation) (Delgadillo-Mirquez et al., 2016).

***Biosorption and bioaccumulation*:** Biosorption is an adsorption of dissolved metal ions and other charged contaminants onto the algal cell surface (polysaccharides, proteins). A part of the compounds is then accumulated into the cell (bioaccumulation) where they may be sequestered, chelated or even transformed (Huang et al., 2025). This bi-surface binding + intracellular internalization facilitates the microalgae to eliminate trace heavy metals (Pb, Cd, Cr, Zn) and certain micropollutants even at low levels. The process of biosorption is usually quick and mostly physicochemical, whereas bioaccumulation is gradual and strain-specific (Abdelfattah et al., 2022).

Biodegradation and collaborative detoxification: A significant number of organic contaminants (remnant cleaning agents, minor organics, dyes/phenolics, many others) are diminished by microalgal metabolism either directly or indirectly through algal-bacterial consortia (Vo et al., 2024). The algae aerate the media (photosynthetic O_2), which in turn sustain aerobic bacteria that break down complex organics; bacterial in turn are able to break compounds down to simplest forms which are absorbed by algae (Abdelfattah et al., 2022). The combination can be more effective at reducing BOD/COD than using either algae or bacteria alone, and is a contributor to the effectiveness of high-rate algal ponds and co-cultures in complex wastewater (Mondal et al., 2022).

Photosynthesis-driven services (CO_2 fixation, O_2 production, pH control): Fixing CO_2 into biomass, microalgae reduce the level of dissolved inorganic carbon, and increase the level of dissolved O_2 during daytime. The O_2 facilitates aerobic biodegradation and CO_2 uptake and bicarbonate dynamics stabilizes the pH oscillation typical of industrial effluents for biological processes and preserves the biomolecules downstream enzymatic reactions (e.g., in transesterification) (Ighalo et al., 2022). Furthermore, because biogas or flue-gas streams are added, biological CO_2 fixation becomes an additional advantage of climate-reduction.

Comparative performance — Indian vs global studies: If the performance of Indian dairy effluents is compared with the global data, two patterns emerge. First, in tropical conditions (Indian conditions, 20–35°C, 9–11h of photoperiod), the volumetric biomass productivities of *Chlorella vulgaris* (0.30–0.65g $L^{-1}d^{-1}$) and *Scenedesmus obliquus* (0.35–0.60 g $L^{-1}d^{-1}$) are also consistently higher than those reported from European and North American open-ponds (0.10–0.30g$L^{-1}d^{-1}$) in previous studies (Goswami et al., 2022; Veluturla & Ravi, 2025). Second, Indian dairy effluent background levels of lactose, lactate and casein are typically high which makes it an ideal medium for mixotrophic growth, and in many cases can increase lipogenic growth by 8–15 percentage points over autotrophic controls, which becomes increasingly important for decentralized, low-light-control, dairy cooperatives in India.

Popular Microalgal Strains used in Phycoremediation

Within dairy wastewater, the success of phycoremediation systems heavily depends on the choice of microalgal strains that is best-adapted to the particular properties of the wastewater being treated (Sisman-Aydin, 2022). Chlorophyta (green algae) and Cyanobacteria (blue-green algae) strains are the most widespread, and some of them have good nutrient uptake, pollutant removal, and biomass productivity characteristics that are important to achieve the phycoremediation effect (Abdelfattah et al., 2022). One of the most researched and most commonly used strains is *Chlorella vulgaris* (Katiyar et al., 2021) which is a preferable option in high-strength effluents because of its vigorous growth at a wide pH scale, its capacity to sustain organic loading and the rapid accumulation of the biomass. In addition, *C. vulgaris* has already shown the potential to remove nitrogen, phosphorus, and heavy metals in the same time, which is why it is particularly relevant in the framework of integrated treatment and biomass valorization (Verma et al., 2022; Talha et al., 2025). Strains of Cyanobacteria,

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including *Spirulina platensis* and *Oscillatoria* are also becoming the focus of the phycoremediation research because of their biomass protein content and ability to survive in high-pH and highly nutritious conditions. *Spirulina*, especially, grows in relatively saline and high pH wastewater streams and also has the added benefit of producing useful co-products of phycocyanin and antioxidants (Koul et al., 2021). *Oscillatoria*, however, has been found to be very effective at eliminating nitrogen and heavy metals present in more intricate effluent matrices, but the filamentous nature may make biomass recovery a problem (Mathimani et al., 2023). Certain microalgal strains are locally isolated, e.g. *spirogyra sp.* (CKW1) and *Cladophora sp.* (PKS33) that can be utilized to treat industrial textile effluents and at the same time produce biodiesel (Waqas et al., 2022). The new microalgal strain, *Chlamydomonas asymmetrica* SAG70.72, has a high nutrients removal rate of pollutants predominantly BOD and COD in the wastewater of the mushroom farm (Alhag et al., 2024). Species of genus *Chlorella* such as *Chlorella fusca* is capable of protecting the water environment by alleviating eutrophication (Arrojo et al., 2022). *Chlorella sorokiniana* also have the ability to extract nutrients and part of heavy metals of waste streams, and it grows rapidly, which is why it is practical in continuous cultivation systems (Ansari et al., 2025). *Clostridium ovis* (COV) can be used in complicated wastewater systems where *Chlorella variabilis* has proved to be extraordinarily adaptable in co-acquiring ammoniacal nitrogen and COD in synthetic dairy effluents together with *Scenedesmus obliquus* (Loganathan et al., 2020). *Scenedesmus obliquus* reported to achieve high nutrient removal efficiencies in batch and continuous cultivation systems (Kisielewska et al., 2020). It has demonstrated a percentage of over 80 novel nitrogen and phosphorus in dissolved urban wastewater trials, as well as high biomass productivity characteristics, which make it an effective remover of wastewater and possible bioenergy utilization (Mennaa et al., 2015). *Scenedesmus obliquus* in mixed algal consortia in research with dairies wastewater was shown to have high ammoniacal nitrogen and COD removal ability, highlighting its promise in the dairy effluent scenario (Loganathan et al., 2020). *Spirulina* are also capable of promoting dissolved oxygen (through photosynthesis) and maintaining balanced microbial communities in phycoremediation systems, though their growth can be more sensitive to certain environmental conditions than some green algae (Loganathan et al., 2020; Kundu et al., 2024). *Spirulina platensis* has been demonstrated to be a useful remover of nutrients, especially nitrogen compounds in dairy wastewater systems and in mixed cultures with *Chlorella* and *Micractinium* outperform the mixed culture in terms of total biomass production and nutrient removal (Hajri et al., 2024). Historically referred to as *Spirulina platensis* and *Spirulina maxima*, these cyanobacterial species (now classified under *Limnospira*) are also explored in wastewater treatment especially in systems aiming for concurrent nutrient removal and biomass production for high-value products such as protein and pigments (Sinetova et al., 2024). Fig 3 represents major clusters of research keywords related to microalgal studies using VOS viewer keyword co-occurrence map.

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Although the most widely studied strains are *Chlorella, Scenedesmus*, and *Spirulina*, other phycoremediation-promising taxa are listed in research literature (table 2), such as *Dunaliella, Botryococcus, Chlamydomonas, Nostoc*, and others, which have a range of different biomass efficiency and resistance to environmental factors (You et al., 2023).

Table 2. Percentage removal efficiency of pollutants by microalgal strains in dairy wastewater.

Microalgal sp.	**Cultivation Medium**	**Pollutant Removal Efficiency**	**References**
Chlorella vulgaris	Raw dairy wastewater	BOD: 85-95%, COD: 70-90% TN: 75-95% TP: 70-90% NH_4^+: 80-95%	Verma et al., 2022; Kumari et al., 2022
Scenedesmus obliquus	Diluted dairy effluent	BOD: 80-92% COD: 65-85% TN: 70-90% TP: 65-85% NH_4^+: 75-90%	Fal et al., 2022; Jaryal et al., 2025
Spirulina platensis	Alkaline dairy effluent	BOD: 65-80% COD: 60-75% TN: 70-85% TP: 60-75%	Chokshi et al., 2016; Arutselvan et al., 2022
Poly microalgal culture (CNSS)	Raw dairy effluent	BOD: 90-96% COD: 80-93% TN: 85-97% TP: 80-92%	Alazaiza et al., 2024
Chlorella kessleri	Dairy wastewater	COD: 70-85% TN: 70-88% TP: 68-85%	Zibarev et al., 2024
Chlorella thermophilia	Dairy wastewater	COD: 72-88% NH_4^+: 75-90% TP: 65-82%	Mohanty et al., 2023
Desmodesmus sp.	Cheese whey mixture	COD: 65-80% TN: 65-85% TP: 60-80%	Salah et al., 2023
Oscillatoria sp.	High-strength dairy effluent	TN: 70-88% Heavy metals: 60-85% COD: 60-75%	Mathimani et al., 2023
Chlamydomonas asymmetrica	Industrial effluent mix	BOD: 75-90% COD: 70-88%	Alhag et al., 2024

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Chlorella sorokiniana	Dairy & agro-industrial mix	COD: 75-92% TN: 80-94% TP: 72-90%	Gauje et al., 2022
Chlorella sorokiniana ASK25 (Indian isolate)	Industrial wastewater	COD: 80-92% TN: 78-90% TP: 75-88%	Veluturla & Ravi, 2025
Scenedesmus sp. (tropical isolate)	Indian dairy effluent	BOD: 88-95% COD: 78-90% TN: 82-93%	Álvarez-Montero et al., 2025

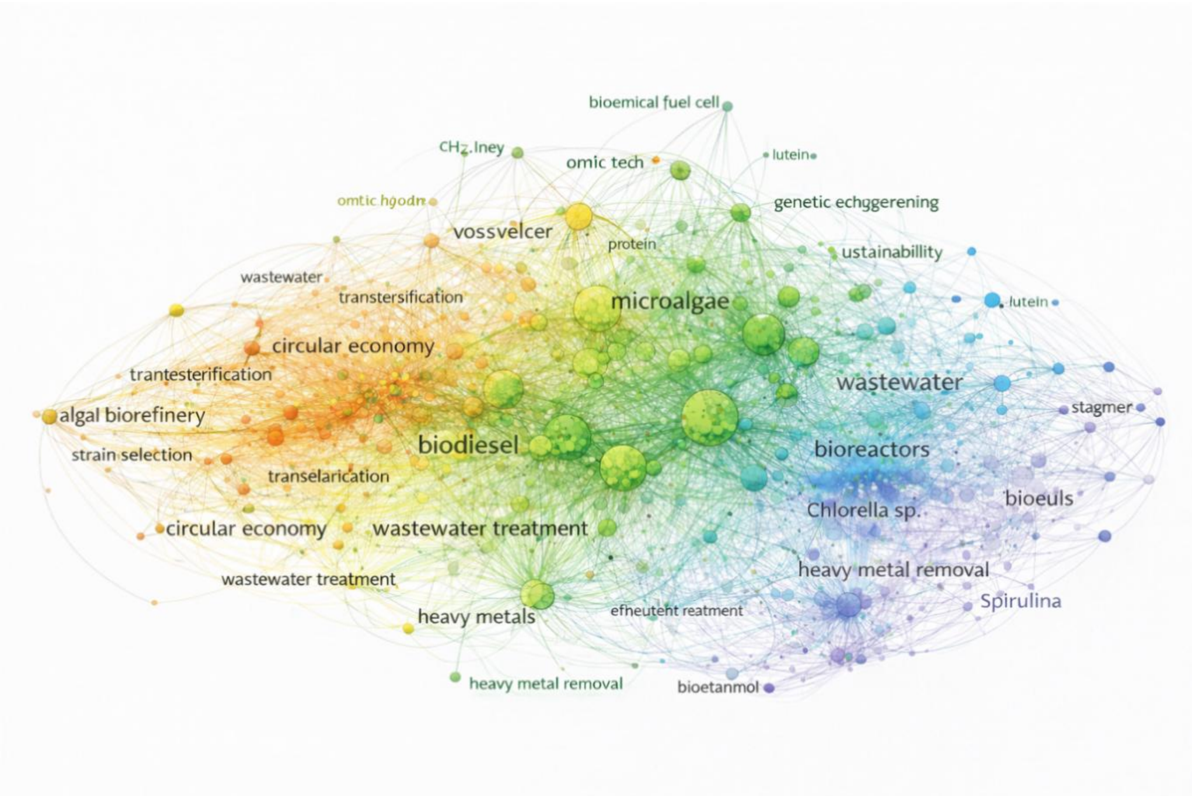

Fig. 3. VOS viewer-based keyword co-occurrence network map illustrating major research publications in microalgal studies.

INTEGRATED BIOREFINERY APPROACH AND CIRCULAR BIOECONOMY

The biorefinery system has become a key in transforming the sustainability landscape of dairy effluents into several resources, and can be managed notably through microalgal phycoremediation. Integrated biorefinery model does not view wastewater treatment as an end-of-pipe solution, but as a resource-based model that transforms waste products into a range of value-added products, which aligns with the concepts of a circular economy (Thomassen et al., 2018; Da silva et al., 2021). The process can result in yielding byproducts with a potential of further valorisation, which would contribute to sustainability and principles of the circular economy (Aksmann et al., 2022). The integrated biorefinery approach will integrate both biodiesel production and provide access to secondary and tertiary products such as biochar, carbohydrates, pigments, bioplastics, nutraceuticals, bio pigments, biogas and animal feed, providing an ecosystem that captures zero-waste valorization or resource efficient system (Paliwal et al. 2019). The National Policy on Biofuels (amended 2022) already allows blending up to 5% for biodiesel and mentions non-edible feedstock such as algal lipids, which opens a clear regulatory pathway from algal pond to forecourt (USDA-FAS, 2024 Biofuels Annual). Through such integration, microalgal biorefineries have certain advantage and limitations, can be employed to give the chance to cycle resources, lessen environmental impressions, and extract socioeconomic benefits in urban and rural dairy clusters (Shah et al., 2021). The most interesting benefits to grow microalgae in dairy effluent are that other types of bioproducts other than lipids can also be produced. The remaining algal biomass of lipid extraction, which is usually high in protein and essential amino acids, can be reused in animal feed, particularly in ruminants and poultry (Saadaoui et al., 2021). Defatted microalgal biomass has been proven to be digestible and nutritionally sufficient, and has become a viable alternative to conventional feed components such as soymeal and fishmeal. Additionally, certain strains, including *Spirulina platensis* and *Chlorella vulgaris* contain a lot of carbohydrates and could be fermented to produce bioethanol or organic acids, which could further increase the economic feasibility of integrated platforms. Another byproduct that is very valuable when a result of pyrolysis of algal residues is biochar. Biochar has the capacity to be utilized as a soil amendment to enhance soil fertility and water retention, but it also takes part in the process of carbon sequestration and in the adsorption of pollutants (Abdelfattah et al., 2022). Processes of biorefinery involving thermo-chemical conversion of algal biomass to biochar and syngas is a well-studied process that has been established in biorefinery configurations that are particularly present where dairy waste management intersects with energy recovery programs. In some experimental environments, biochar appears to be effective in the adsorption of the residual nutrient and heavy metal content as well, and in combination with phycoremediation units, it can enhance wastewater polishing (Abedi et al., 2023). Other valuable uses of algal strains include the production of high-value pigments and antioxidants including 2-carotene, Phycocyanin, astaxanthin and chlorophyll. The compounds find numerous uses in pharmaceutical, cosmetic, and food sectors, and the fact that they can be extracted out of dairy wastewater-grown algae provides an additional dimension of commercial prospects (Fernando et al., 2021). Similar concentrations of pigments have been observed between *Scenedesmus obliquus* and *Spirulina* grown in effluent media compared to those grown in synthetic media, which suggests that wastewater can be used as a growth medium without affecting the quality of the products (Roy et al., 2025). The incorporation of anaerobic digestion schemes with microalgal biorefineries offers another aspect to circular bioresource recovery. The liquid phase with a high organic content that is produced upon the extraction of lipids in algal residue could be co-digested with dairy sludge to produce biogas, which could subsequently provide energy to the same

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system, forming a self-sustaining cycle (Michalski et al., 2024). A number of pilot-scale systems have shown that it is possible to couple phycoremediation with biogas digesters, with the CO_2 produced by biogas combustion being captured by algal cultivation units, thereby boosting biomass productivity by capturing carbon (Kusmayadi et al., 2021; Djarot et al., 2024). This recycling of nutrients and energy is the core idea of the circular economy ethos where each product is reused in the production cycle as an input. Despite these encouraging factors, full integration of algal biorefineries in India remains in its early developmental phase, mostly restricted to research laboratories and experimental consortia. The local infrastructure, policy incentives, and cross-sector cooperation between dairy producers, waste managers, biofuel companies, and agricultural cooperatives are crucial to the scalability of such systems. Nevertheless, the Indian government has been encouraging bioenergy and clean technology via programs like the National Bio-Energy Mission and GOBARdhan Yojana, creating a golden chance to mainstream algal biorefineries as rural energy and waste management infrastructure (Chanana et al. 2023).

Multi-Product Valorization Tailored to the Indian Context

A biorefinery based on Indian microalgae has the potential to provide five concurrent value streams, which are directly linked with rural socio-economic activities: (i) biodiesel/FAME blended with HSD for cooperative-fleet vehicles and milk-collection trucks, (ii) defatted biomass for buffalo and poultry feed substitution, where the protein content (28–40% DW) competes with imported soybean meal, (iii) phycocyanin and carotenoid pigment from Spirulina/Chlorella consortia, which have premium price in domestic nutraceutical market (BIRAC, 2024), (iv) algal biochar (soil amendment) in adjacent socio-economic activities like paddy in Punjab and sugarcane in UP and Maharashtra, and (v) treated polished water for non-potable use for cleaning within the biorefinery site or for irrigation and cultivating fodder/food.

Integration with Existing ETPs and Anaerobic Digestion

Most importantly, the proposed Indian model is not a ‘green-field’ alternative to the existing ETPs; it is merely a polishing and recovery layer. Anaerobic digesters (UASB or fixed-film) of biogas with a capacity of 8–25 m^3 of biogas per m^3 of effluent are already in use by most cooperative dairies. The ability of the biogas-combustion flue gas (10-15% CO_2) to route into the adjacent microalgal raceways, which results in carbon sequestration, increased algal growth and pH stabilization of the pond, has been observed during the pilot studies by Kusmayadi et al. (2021) and Aditya et al. (2022). The post-AD liquid digestates, which is generally pumped out to open drains these days, is utilized as the nutrient rich feed for the microalgal raceways without needing to use any synthetic media. The basic retrofit structure suggested in Fig. 4 is Anaerobic Digester (AD) – CO_2 – digestate – Microalgal HRAP (M-Algae) – harvested biomass – on-site lipid/biorefinery.

India-Specific Cooperative and SME Models

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Three implementation archetypes are feasible in India: (a) Co-operative anchor model – with larger cooperatives (Amul/Banas, Mother Dairy, Nandini, Aavin, Verka) having a central module of ETP/PBR sized at 1–5 MLD, with existing on-site engineering manpower; (b) Cluster decentralized model – wherein 5–20 small foot print SMEs in a peri-urban cluster (Tajpur in Ludhiana, Kolar in Karnataka) operate a community biorefinery of ETP/PBR of size 1–5 MLD, with a Producer Company or a Self-Help Group managing the entire cluster; and (c) Village-scale GOBARdhan-integrated model – where the digestate–biogas pair from GOBARdhan plant is used as an input for the central ETP/PBR sized at 1–5 MLD, with digestate being used for irrigation and biogas being used in ovens, biogas chambers, or gas power plants operated by the community. The viability gap funding from NABARD, CSR contribution and the Bio-E3 policy incentives for manufacturing can be provided through different combinations to each archetype (BIRAC, 2024).

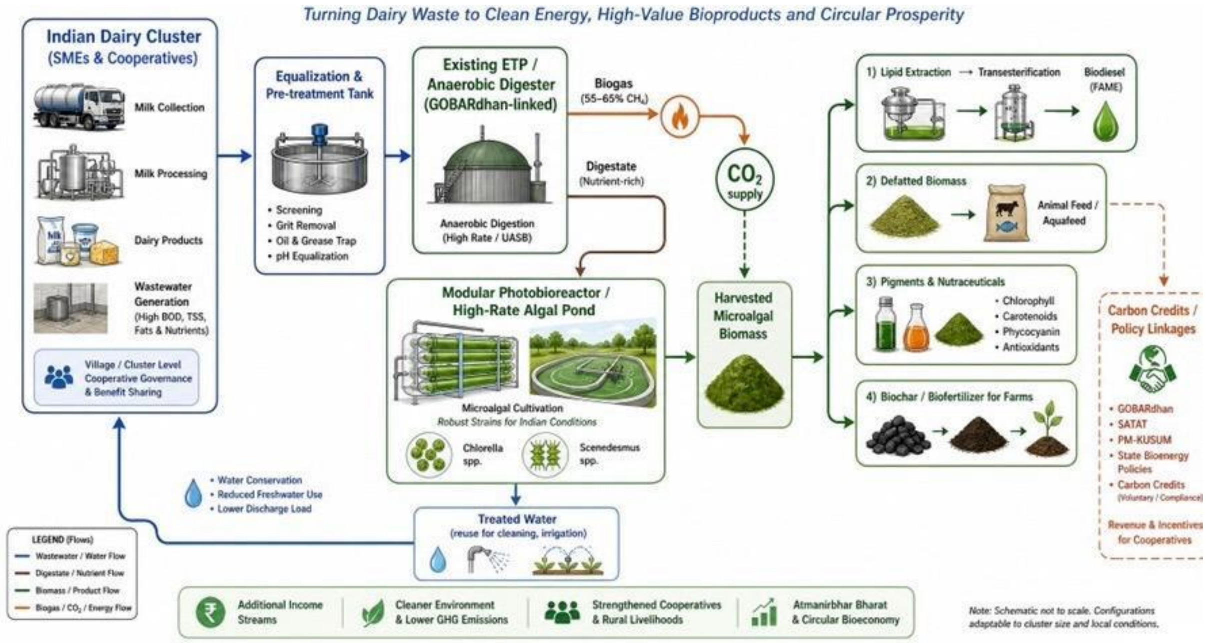

Fig. 4. Proposed integrated microalgal biorefinery system for Indian dairy cooperatives.

CHALLENGES SPECIFIC TO IMPLEMENTATION IN THE INDIAN DAIRY SECTOR

The implementation is a challenge in the Indian dairy sector because of various technical roadblocks. The context of Indian implementation forces and constrains a set of tightly-knit constraints for which dedicated, integrated attention is needed.

Seasonal Variation and Climatic Heterogeneity

Climatic zone variability in India is from cool dairy belt in the sub-Himalayan region (winter minima 4–8 °C in Punjab and Haryana) to hot semi-arid regions of Gujarat and Rajasthan (summer maxima >45 °C) and humid coasts of Kerala and Andhra. In northern regions (December–February), open raceways suffer from lower rates of growth (40–60%) and in May–June, growth rates are affected by heat stress and evaporation losses (up to 8 mm/day) that can affect pond hydraulics (Veluturla &

Ravi, 2025). This is mitigated in hybrid pond + closed-PBR designs with thermal mass buffering, and HDPE liners (at 30-40% capital premium).

CO_2 Supply Logistics

In-situ CO_2 from flue gas is available for large cooperative dairy operations, but is not available for small dairies. The innovative pathway adopted are: Co-location of adjacent agro-industries like Sugar Mills and Distilleries, Bicarbonate spraying in irrigation tanks and shared logistics of CO_2 for CO_2 based compressed-biogas (CBG) plants (World Biogas Association, 2024; PIB, 2025).

Capital Constraints and Financing

Modular bio refinery is estimated conservatively at INR 4.5–7.5 crore CAPEX (approx. USD 540K–900K) which is beyond the capacity of typical SME dairies. The suggested financial instruments are: NABARD's Dairy Processing & Infrastructure Development Fund (DIDF); MoFPI Pradhan Mantana Kisan Sampada Yojana; and Bio-E3 Policy thematic-cluster grants (BIRAC, 2024). Carbon-credit revenue can cover 12-25% of the lifecycle cost for cooperatives (ICAR-CRIDA, 2025).

Policy and Enforcement Gaps

The pollution control architecture in India is correct in theory (Water Act 1974, EP Act 1986, CPCB norms, FSSAI guidance) but defunct in practice. Algal biofuels are not subject to a specific tariff or feed-in mechanism, there is no national algal-product safety standard, and there is no simplified consent-to-operate (CTO) pathway for algal raceways as 'green ETPs'.

TECHNO-ECONOMIC FEASIBILITY AND LIFE-CYCLE CONSIDERATIONS (INDIAN CONTEXT)

Capital and Operating Cost Structure for an Indian 1 MLD Biorefinery

The cost engineering of the microalgal biodiesel plants has come a long way (Wiatrowski et al., 2025 NREL; Veluturla & Ravi, 2025). In an indicative 1 MLD dairy-effluent biorefinery, the unit-cost vectors for the different works can be adapted to Indian factor costs as follows: civil works and pond/PBR works (35-40); harvesting and dewatering (20-25); instrumentation/automation (8-10); balance-of-plant/ EPC margin (10-15). The total CAPEX is estimated at INR 4.5-7.5 crore for 1 MLD throughput (biomass productivity of 18-22 g m-2 d-1 and lipid content of 28-35%). OPEX is dominated by labour (≈22%), nutrients/CO_2 supply (≈18%), energy (≈25%) and harvesting consumables (≈15%) (Khoo et al., 2020; Veluturla & Ravi, 2025).

Carbon Sequestration and Carbon-Credit Potential

The microalgae used for CO_2 fixation for 1 kg of dry biomass is about 1.83 kg of CO_2 per kg of dry biomass (Saranya and Shanthakumar, 2021). With an operating rate of $22 gm^{-2}d^{-1}$ and a biorefinery footprint of 0.4 ha, a 1 MLD biorefinery sequesters ≈58 tonnes CO_2-eq per year. This is a non-trivial cash-flow, a monetizable benefit, that adds USD 460-870 per MLD effluent per year (annual effluent production of 1000 MLD for a 10-year project) to the project's IRR at a conservative carbon credit price of USD 8-15/t CO_2-eq under India's

Carbon Credit Trading Scheme (CCTS, notified 2023).

Payback and Sensitivity Scenarios

The simple payback period for a 1 MLD facility is calculated at 5–8 years for base case conditions and 3.5–5 years with optimistic conditions, including maximum use of defatted feed, maximum utilization of the pigment (co-cultivation of Spirulina) and maximum carbon credit presentable under GOBARdhan support as subsidy. According to sensitivity analysis, three major economic levers are the lipid content, harvesting cost and biodiesel offtake price. Biodiesel produced from algal is reported to have life cycle GHG emissions of 0.8–1.4 kg CO_2-eq/kg, which are far lower than conventional HSD (3.1 kg CO_2-eq/kg) and Karanj biodiesel (1.9–2.4 kg CO_2-eq/kg; Kumar & Pal, 2023).

FUTURE PERSPECTIVES, POLICY RECOMMENDATIONS AND IMPLEMENTATION ROADMAP

The recent development in microalgal phycoremediation as a combined technology to treat wastewater and produce biofuels creates a prospect of scaling and optimizing the technology to be applied in a large scale in the dairy industry in India. The concept the circular bioeconomy can be used to enhance the current waste water treatment technologies because they could be substituted by this phenomenon of microalgal phycoremediation. Nevertheless, to realize the full potential of this strategy, technical and economic bottlenecks should be overcome, but innovation at the border of biotechnology, systems engineering, and policy should also be embraced. One of the most significant innovations is genetic engineering in microalgae, which is one of the frontiers. By genetically manipulating the genomes of algae to increase their ability to accumulate lipids, nutrients, and withstand stress, scientists can greatly increase the biomass and biodiesel production even when the wastewater is not favorable. Genetic engineering has already made possible overexpression of acetyl-CoA carboxylase and other lipid biosynthesis pathway genes in *Chlorella* and *Scenedesmus* strains, which have led to an increase in lipid content without any reduction in growth rates. Parallel to this, modular photobioreactor systems are also appearing as a scale-up alternative to substitute or supplement conventional open pond cultivation. These closed, adjustable systems enable better regulation of the environmental conditions, including light, temperature, and CO_2 provision, and mitigate the negative effect of seasonality that is prevalent in Indian dairy clusters. In addition, modular bioreactors can be scaled to space-constrained regions, and they can easily be installed in dairy processing facilities or effluent treatment plants. They are flexible in their design, facilitate process standardization, simpler automation, and enable biomass harvest cycles to be more reliable, all of which lead to reducing the uncertainty in operations and enhancing system resilience. Positive institutional cooperation and policy despite technological readiness can help in making microalgal biorefineries successful in India. Regulatory support that encourages bioenergy adoption and the promotion of decentralized wastewater treatment solutions is much needed at this time. These include capital subsidies to install algal bioreactors, feed-in tariffs on algal-produced biofuels and expeditious approval procedures on co-product commercialization. One of the most promising models, public-private partnerships (PPP), in which joint stakeholders such as dairy cooperatives, biotech companies, governmental research institutes, and government agencies would invest and operate in combined algae treatment systems. Such collaborations can help in bridging the gap between laboratory research and commercial application and also facilitating transfer of technology to smaller dairy units and rural entrepreneurs.

Policy and Financial Recommendations

To accelerate the adoption of algal effluent treatment plants (ETPs) in dairy clusters, the government should implement capital subsidies of 30-40% under existing schemes like the Dairy Infrastructure Development Fund (DIDF) by NABARD and PM-Kisan Sampada Yojana of MoFPI. Additionally, the National Policy on Biofuels needs to make a specific mention of algal biofuels, providing definite offtake commitments and feed-in tariffs equivalent to the 2nd generation bioethanol. Convergence of policies is also suggested by algorithmic projects with the GOBARdhan Yojana, allowing correlation in the evaluation, funding and monitoring of algal raceways and plants for Compressed Biogas (CBG) under a single Cluster Development Window. The smallholder dairy clusters should be enabled to cluster algal carbon sequestration into a bankable carbon credit project based on the ICAR-CRIDA (2025) voluntary carbon market for agriculture to unlock additional revenue streams. In addition, the Bureau of Indian Standards (BIS) should provide technical specifications for the modular ETPs utilizing microalgae and the Central Pollution Control Board (CPCB) should bring in a simplified Consent to Operate (CTO) checklist which will allow ETPs using microalgae to be classified as 'green' tertiary treatment add-on. Lastly, the operations of microalgal biorefinery should be included with the Skill India PMKVY job roles in Agriculture Sector Skill Council (ASSC) in order to develop skill base.

Path to Implementation – Indian Dairy Clusters (2026-2035)

Algal biorefineries can be rolled out in the dairy clusters in India in three stages:

Phase I (2026-2028) – Demonstration: Six lighthouse pilot projects will be set up, each in one of the major dairy belts, namely Anand, Karnal, Ludhiana, Kolar, Lucknow and Hyderabad, at the cooperative dairies. These pilots will test the techno-economic viability, and provide high-quality data of seasonal performance.

Phase II (2028-2031), winning products from Phase I will be scaled up to 50-100 SME dairy clusters. There will be strengthening of the integration with the programmes of the state level under GOBARdhan and CBG schemes, as well as refinement of BIS standards, based on actual data from the first pilots.

Phase III (2031-2035) – National Mainstreaming: Algal biorefineries will be incorporated into all new dairy ETPs as standard. Plants having the capacity of more than 0.5 MLD will be subjected to mandatory adoption by FSSAI and CPCB. These systems will also be linked to the national carbon registry and the Ethanol Blending Programme to realize the maximum environmental and economic gains.

CONCLUSION

The literature reviewed in the present paper demonstrates the versatile nature of microalgal phycoremediation as a rationalized, sustainable, circular, and technologically feasible method of treating dairy wastewater in India. Through critical examination of physicochemical properties of effluents, the most appropriate algal strains, biochemical yield profiles and transesterification reactions in the production of bio-diesel, it emerges that the integration of microalgal systems in the management of dairy waste can be of dual advantage; environmental remediation and biofuel production. Strains such as, but not limited to, *Chlorella vulgaris, Scenedesmus obliquus,* and *Spirulina platensis* have been shown to have strong nutrient uptake abilities and significant lipid accumulation rates even under conditions of stress. Additionally, the transition to integrated biorefineries and circular economy designs has created an opportunity whereby, various value chains, such as biodiesel, animal feed, biochar, and pigments, can be derived out of one waste stream and achieve zero-waste results. This synergy between the microalgal remediation treatment and the anaerobic digestion, nutrient chain and pigment recovery makes the microalgal remediation approach more cost-effective especially in decentralized and rural applications. Despite these positive performances, a number of problems have been incurred and they are; seasonal variation and excessive capital cost, absence of dynamism in policies and illiteracy at grass root level. The following solutions like introducing digitally advanced and modular bioreactors will promote such issues. Along these, the strengthening of the non-academic-industry-business-government interrelations will also be a significant part in sustaining the success in the labs in scaled applications that will be valued at the field level. In conclusion, it is not the need but ecological need, socio-economic opportunity to apply phycoremediation of microalgae. Dairy industry in India is rising, and putting a strain on water resources; therefore, this win-win solution gives an opportunity to transform effluent liabilities to renewable resources. Strategic implementation can consider becoming a global leader by developing algae-based scale-based circular economies that can transform waste, to become not a problem, but a resource of sustainable development that is scientifically and policy-supported. When it comes to phycoremediation, microalgal technology is no longer in the lab and has become a technology deployment-ready and relevant to India's 239 MT milk economy and 275+ MLD dairy effluent footprint. The evidence put together in this review shows that Indian strains can remove nutrients by >90% and produce >250–360 L of biodiesel per tonne of biomass under realistic conditions in India, with the policy frameworks (GOBARdhan, SATAT, the Carbon Credit Trading Scheme, Bio-E3 Policy and the National Policy on Biofuels) already providing a good regulatory framework. What is still lacking is the convergence in operation: the standardized modular hardware, dedicated financial windows for SME dairy clusters, and a step-by-step roadmap. The milk effluent from the Buddha Dariyas, which now make our Buddha Dariyas acidic, can today drive the very milk collection vans that fill the cooperatives and, in the process, create water, energy, feed and rural livelihood.

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Jyotsna Mishra: Responsible for Comprehensive literature review and prepared manuscript. Vikram Singh: Expert insights, guidance support, Conceptualization, Revision and editing. Vikas Kumar: Literature search and writing. Sonia Singh: Editing and design. Sarvesh Yadav: Literature search

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