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Characterization of dairy waste and its valorization for eco-safe waste management and development of value added products: Challenges and opportunities

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Abstract: *Dairy industry generates huge amount of waste and by-products during processing and production of milk and milk products, which can be re-utilized for resource optimization, recycling and ecological sustainability of the dairy industry. Since, these so-called by-products (Dairy waste) are rich in mineral-nutrient and other dietary components that are essential for human nutrition, these can be transformed into value-added products to generate wealth from waste in an environment friendly manner besides alleviating-reducing the GHG emissions that often accompany the dairy waste. Microbial valorization strategies like fermentation, enzymatic hydrolysis and biosynthesis can be used to produce a large variety of value-added bio-products like biofertilizers, biopolymers, biofuels, biosurfactants, bioactive compounds, organic acids, enzymes and others. The present paper critically examines the information available in respect of challenges and opportunities available for economical and environment friendly management of the dairy wastes. The manuscript dissects the nutritional characteristics of the dairy waste and discusses different strategies for their microbial biotransformation and value addition. By, leveraging the inherent potential of dairy waste, this paper contributes in finding innovative, sustainable and economically viable pathways for converting waste to valuable resources for various industrial applications and revenue generation.*

Keywords: *Dairy waste, bio-products, mineral nutrients, microbial conversion, bio-transformation, GHG emission, bioplastics*

1. INTRODUCTION:

The dairy industry plays an important role in food production, economy generation, and rural employment worldwide. They contribute in fulfilling the sustainable development goals (SDG) 2 global food security by providing self-sufficient nutritional food and promoting sustainable agriculture practices. Due to advancements in breeding, nutrition, and technology, the dairy industry has reflected remarkable growth in the past few decades. Innovations in value-added product development such as probiotic functional food, flavored cheese, reduced sugar, and low-fat dairy products have highlighted the industry's adaptability to evolving customer choices integrating modern health and lifestyle preferences. India being the largest milk producer country contributes 24% of global milk production leading to a 61% increase in milk production in the last 8 years, producing 221.1 million tonnes in the year 2021-22 (1). Excellence in the E-commerce area, improved retail operations, enhanced cold chain facilities, and diverse quality enriched dairy products have boosted the size of the dairy industry reaching Rs.16792.1 billion in 2023 (2,3). The leading growth in the dairy sector is dominated by liquid milk followed by probiotic drinks and yoghurt, while A2 (βcasein) milk shows the fastest growth in milk market sector. (4,5) Besides all the progress and innovation in the dairy industry, the cause of major concern in today's era is waste management. Consistent rise in the number of dairy units has not only produced milk and milk products but also has given rise to dairy waste causing harm to the environment.

1.1 Dairy waste: A quantitative analysis

Among the entire food sector dairy sector tends to generate a maximum quantity of waste due to the consumption of huge amounts of water to run a single dairy plant. To process 1 liter of milk, nearly 6-7 liters of water is required which later becomes a source of waste (6). Milk and milk item production fulfills the world's nutritional needs on the other hand it concurrently produces dairy waste three times the quantity of milk production. (7,8) In general, 4-11 million tonnes of dairy waste is produced globally every year including solid and liquid waste. Globally around one-third of food produced for human intake is lost or wasted contributing 1.3 billion tons of food wastage. (9,7). Milk is a perishable item, around 18.1% of annual milk production is wasted or lost due to a lack of facilities for storage and transportation (10). Europe accounts for wasting approximately 29 million tonnes of dairy products annually (11,8). Customers are the prime factor in the wastage of food products when compared to any stage of the supply chain. Roughly around 40 billion kg of food is wasted globally (12). Swedish residential drains around 8kg of dairy products per person per year (7). American families waste 25% of their purchased food and beverage items. General household waste contributors are fruit and vegetable22%, dairy products 19%, more specific in dairy products 4.76 billion liters of fluids milk and 2.5 billion liters of other dairy products are wasted (13,14,12). The dairy industry in Poland consumed around 278hm^3 of water annually which accounted for 35% of water consumption in the food industry in 2014 (15,16). European Union generates $192.5 \times 10^6 m^3$ of dairy wastewater annually among this 49% is due to cheese production while milk, acidified milk, and butterfat products accounts for 19%, 18% and 13% respectively. 6 nations Germany, Poland, France, Netherland, Spain, and Italy combine produces more than 73% of wastewater while followed by Ireland and Luxembourg generating 1441L and 6L of wastewater respectively (17). 80-90% of milk used in cheese production becomes a waste, resulting global production of 180-190 million tonnes of whey waste annually, in which 100 million tones itself accounts for cheese whey. (18,19,20).

The treatment of each liter of milk produces 1-3 times of dairy waste producing 3.739-11.217 million m^3 of waste annually. Maximum waste generation is from cheese manufacturing about 9kg of whey waste per kg of cheese (21). The effluents treatment plant in a fully functional dairy plant generates about 250-350kg of sludge from processing of 5lakh liters of milk. Managing these wastes is a challenging task as it may cost up to 60% of the overall expenses of milk processing. (22,20). To solve the problems for this emerging dairy waste, an innovative sustainable approach for the vulnarization of such large-scale dairy waste is by adopting biological treatments is highly desired which boosts the researchers to find different ways for bio-reduction of dairy waste or reuse and recycle the potential source of energy imbibed in these wastes by introducing different biological techniques and promoting zero waste generation.

Recent research has focused on technological innovations in transforming edible dairy bi-product waste into consumable food products like whey protein supplements (8), lactose-enriched confectionery (23), and biogas production (24) whereas advancement in the research from non-edible dairy waste is pinpointed in sustainable environment growth such as biofertilizer for soil amendments (25), biomass for energy (26), biofuel production (27) and building materials (28) Hence, the research paper provides review on waste generation, its composition and augmenting bio-techniques for producing value-added products from dairy waste.

1.2 Dairy waste: production, composition and characterization

Dairy waste is generated at various steps of processing, packaging, storage and transportation, and cleaning of dairy equipment like pasteurizers, cream separators, butter churners, homogenizers, tanks, silos, and others which is represented in (**Fig 2**). In addition to this spoiled, spilled, expired, or low-quality milk products along with by-products like whey from cheese, paneer, and curd sections also released during production which becomes a source of dairy waste. (29). Various sources of dairy waste generation are illustrated in (**Fig 1**) Dairy waste can be broadly classified into 2 groups mainly liquid waste (whey, washed water, cleaning agent) and solid waste (Expired milk and milk products, packaging material, sludge) which can further be categorized into edible by-product waste (cheese whey, buttermilk, yoghurt whey, cream residue) and non-edible dairy waste (Packaging material, sludge, dairy scum, untreated water, cleaning agent, spoiled milk). Dairy waste contains a potential source of nutrients like fat, protein, lactose, vitamins, and minerals represented in (**Fig 3**). which when exposed to the environment not only causes air, water, and soil pollution but can also trigger climate change due to eutrophication, methane emission, increasing toxicity in the environment. (30).

The dairy industry generates either fat-rich dairy waste like scum, cream residue, and clarified butter sediments, or less fat dairy waste like milk, and whey (31,7). Manufacturing of 1kg cheese generates 9 liters of whey as bi-product waste which can cause acidification and eutrophication harming water bodies when disposed untreated. Also, high-fat dairy waste slows down the natural degradation causing hindrance in the waste water treatments. (32) Furthermore, high loads of organic and inorganic constituents in dairy waste enhance the BOD (1000 to 2000g/L) and COD (1500 to 3000g/L) (33) level when disposed of in the environment without any prior treatments. The COD value per kg of lactose, protein, and fat is equivalent to 1.13, 1.36, and 3kg COD respectively (7). In addition to this, a rich number of microorganisms including pathogens in dairy waste can invade humans through various means and can increase the risk of disease and infection (34). Dairy waste includes nitrogen and phosphorus contents of 70-100 mg/L and 10-60mg/L respectively when leaches off to the aquatic ecosystem disrupts the ecological balance causing a threat to biodiversity (32,33,34). A detailed list of characteristics of dairy waste by-products and dairy effluents are mentioned in (**Table 1**)

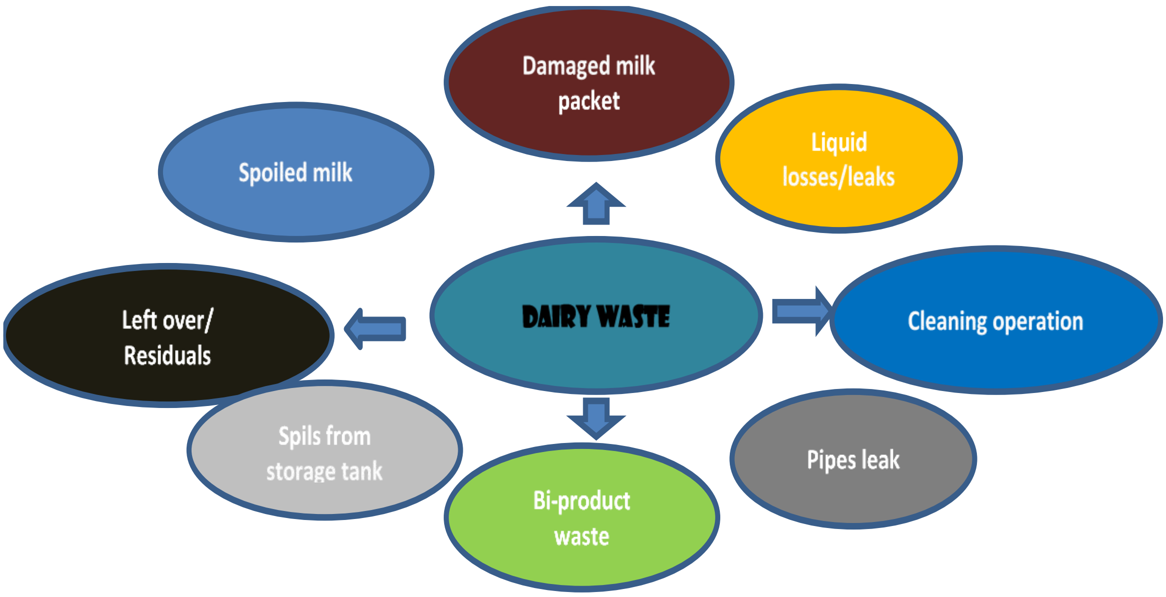

Fig 1: Sources of dairy waste generation

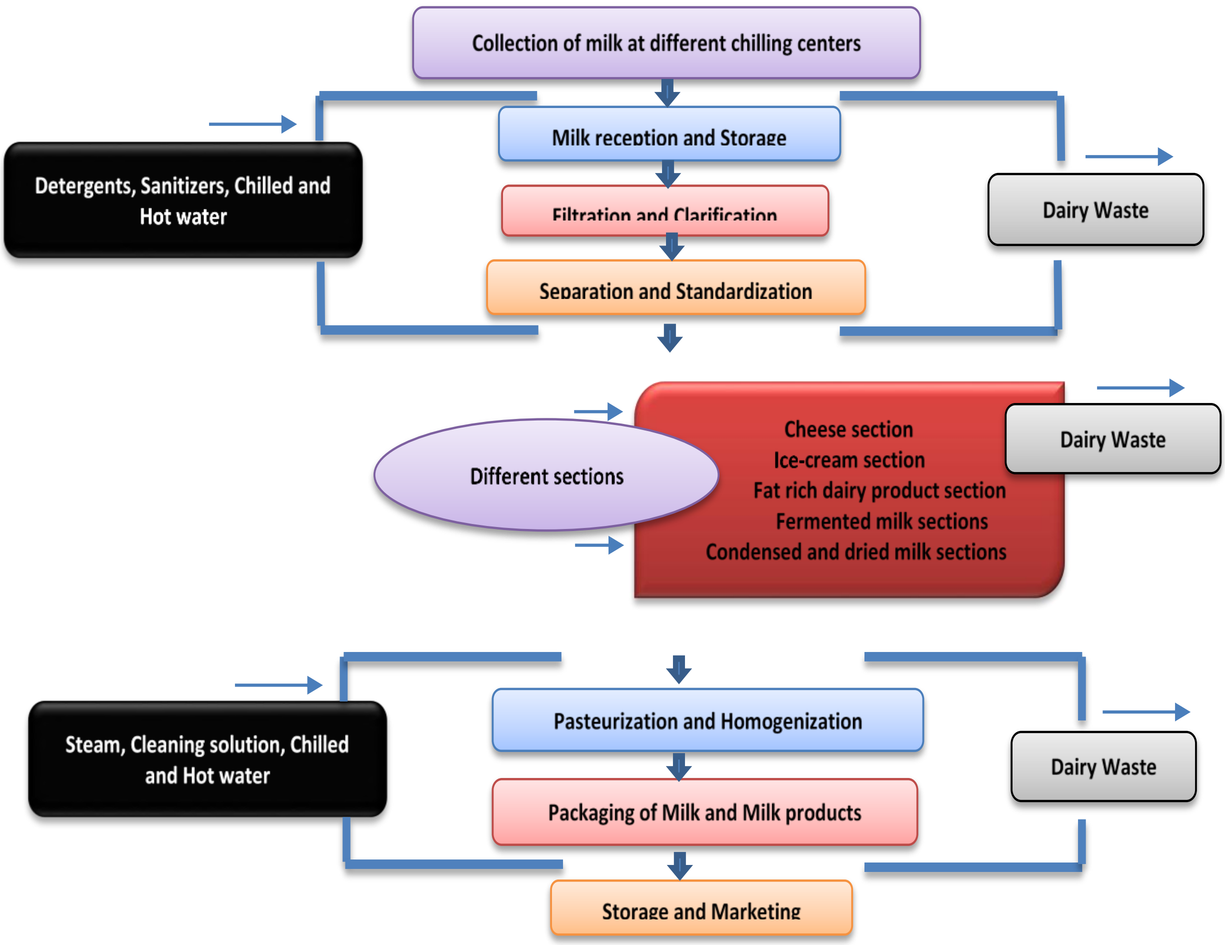

Fig 2: Process of dairy waste generation

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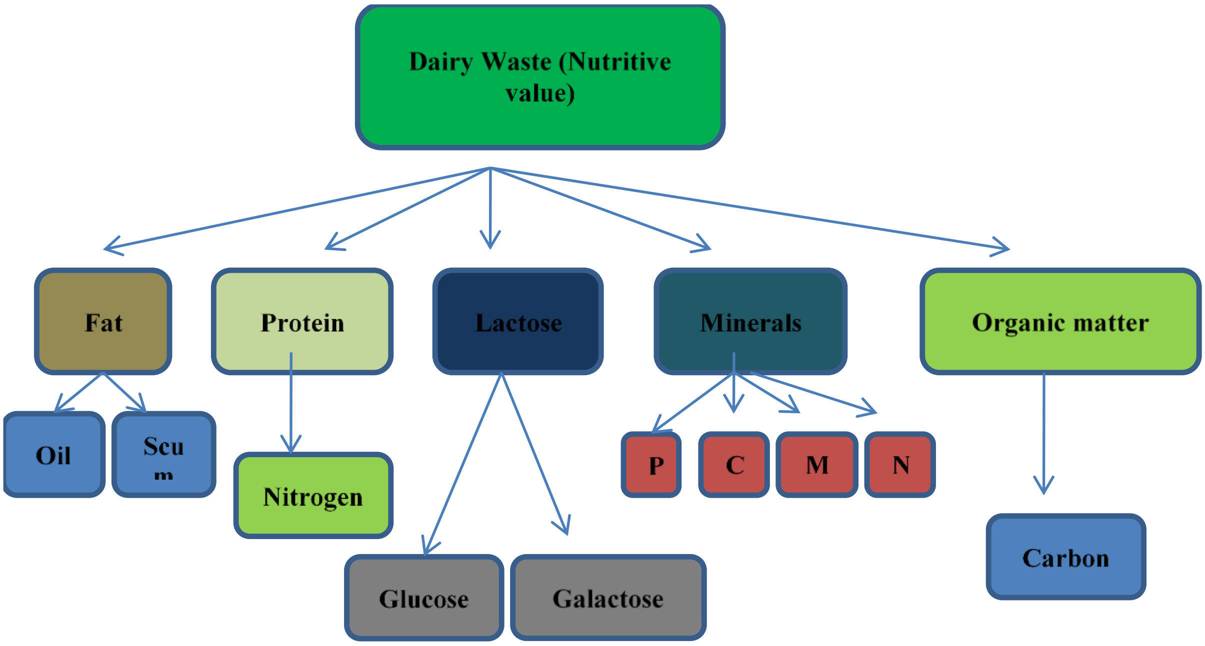

Fig 3: Potential value of dairy waste

Table 1: Biochemical and nutritional characteristics of dairy by-products and effluents

Parameter	Wastewater types			References
	Cheese whey waste	Untreated dairy effluent	Mixed dairy waste	
BOD (g/L)	51.6- 55.9	0.65-1.71	0.24-5.9	(35,36)
COD (g/L)	72-77	1.448-2.52	0.5-10.4	(35,36)
TDS (g/L)	3.44	0.67-2.533		(37,38)
TSS (g/L)	0.19-2.5	0.61-1.670	0.06-5.80	(33,38,35)
TS (g/L)	59.76	1.310	0.70-7.0	(7,39,35)
pH	3.30 -9.5	5.28-8.67	-	(7,33,38)
Alkalinity (mg/L)	1.8 caco3	0.44-0.66	0.32-1.2	(40,35)
Chlorides (g/L)	0.246	0.17-0.44	-	(41,35)
Fat (mg/L)	0.05	500	-	(37,42)
Protein (g/L)	1.48	0.38	-	(7,43)
Sodium(g/L)	0.745	0.215-0.387	0.1-2.3	(44,40)
Lactose (g/L)	35.28	0.02-0.10		(7)
Calcium (g/L)	0.048	0.09-0.15	0.013-0.130	(44,40)
Manganese mg/L	-	Nil	0.03-0.45	(44)
Potassium (g/L)	0.041	0.017-0.05	0.01-0.18	(44,40,35)
Nitrogen (g/L)	0.018–0.83	0.043	0.01-0.66	(33,45,35)
Phosphorus (g/L)	0.28-1.45	0.011	0.1-0.6	(46,45)
Iron (mg/L)	-	1.04	0.5-6.75	(46,45)
Magnesium (g/L)	0.78	0.00423	-	(46,45)
Sulphate(g/L)	0.43	0.395	-	(46,35)
Phosphate (g/L)	1.455	0.006-0.023	-	(46,40)
Nitrate (g/L)	-	0.026-0.054	-	(40)
Zinc (mg/L)	-	1.57	-	(45)
Color	Yellowish	Pale white	-	(47)

Temp (°c)	30-50	22	-	(47)
Turbidity (NTU)	536-659	25	-	(48)

2. Dairy waste management: present status, opportunities and limitations

Various strategies for dairy waste management are being practices however, they often have accompanying limitations, which are discussed in the following section.

2.1 Conventional treatment methods and their limitations

Some dairy industries directly dispose of their waste in the nearby water bodies which is not recommended as its consequences may give rise to loss of aquatic biodiversity, increase in chemical pollution and disease transmission, causing human health risk and water contamination (49). Therefore, various treatment methods are adopted which can be broadly categorized as physico-chemical and biological treatment methods which is represented in (**Fig 4**).

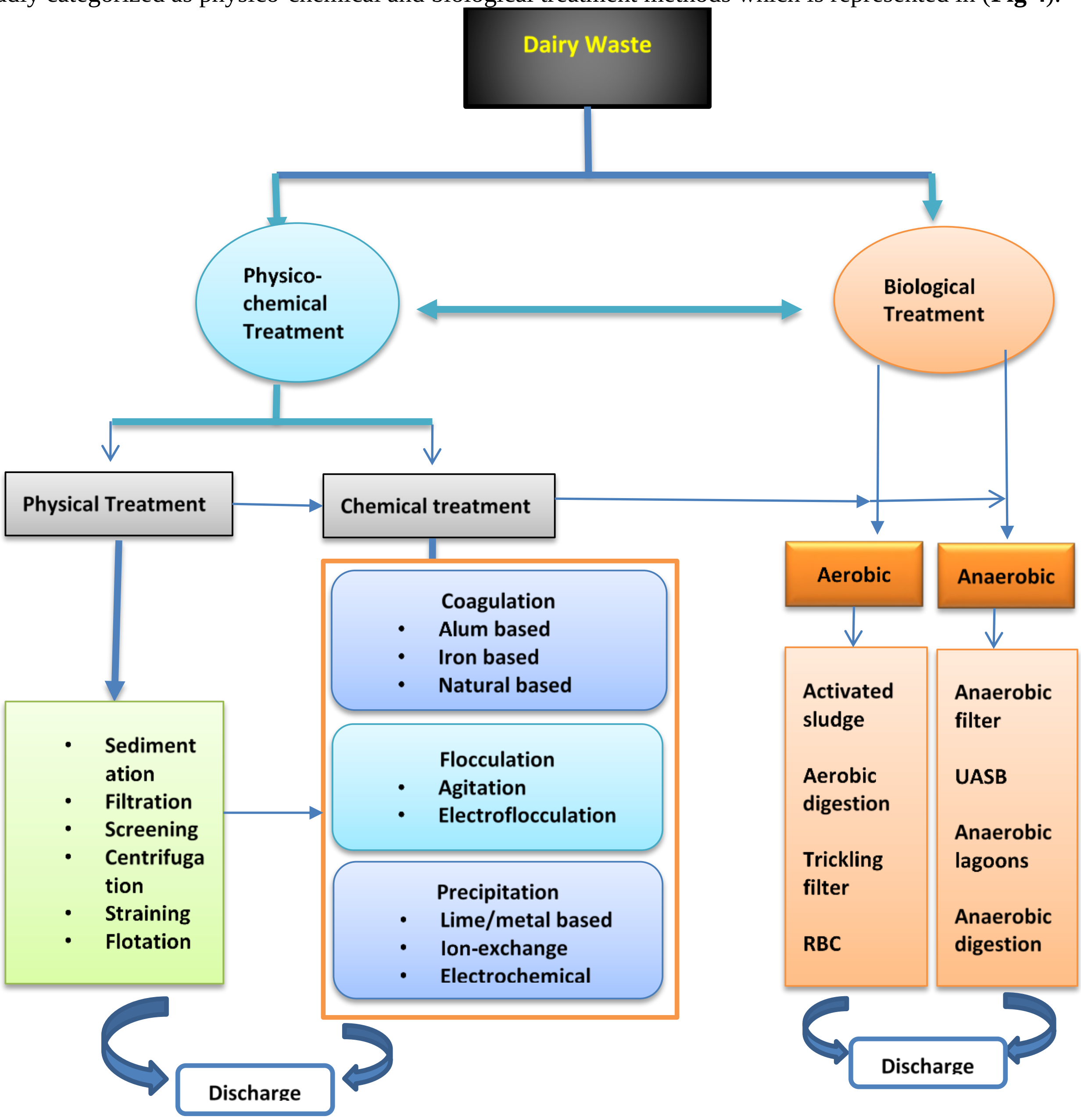

Fig 4: Dairy waste treatment methods

2.1.1 Physico-chemical methods of dairy wastewater treatments are the integration of mechanical and chemical mechanisms to reduce pollutants. Mechanical treatment methods like sedimentation, filtration, screening, centrifugation, and straining can be pre-treatments adopted in combination with chemical treatment including coagulation (such as aluminum-based, iron-based, organic or natural-based) flocculation (such as agitation or electro flocculation), and precipitation (such as lime or metal based, ion exchange or electrochemical type) to achieve high efficiency and better effectiveness. The aforesaid waste treatment methods help in reducing pollutants and mitigating the risk of environmental impact. However, this method may not completely eliminate the contaminants and can vary depending on the characteristics of dairy waste. Unlike biological treatment methods, the pathogens may not be completely eliminated by adopting physico-chemical methods. Such treatment methods for the removal of soluble COD are limited due to their low ability for COD elimination (35). Although this method removes emulsified particles but requires an additional step for reagent addition leading to an increase in the treatment cost (35). Adopting physico-chemical methods helps in reducing milk colloidal particles but major challenges lie with the complete removal of fat and oil from the cheese and butter section (35). However, adopting this method can result in generating residual sludge which is furthermore difficult to dispose of and recycle (50). Moreover, physico-chemical treatment strategies lack the complete removal of nitrogen and phosphorus compounds from dairy waste (51). The major drawback of adopting these treatment strategies is that potential nutrients present in dairy waste are lost which can be innovatively used for converting into different valuable products and contributing towards environmental sustainability. Biological treatment methods are taken in addition to this for more effective results.

2.1.2 Biological methods of dairy wastewater treatment involve the use of microbes to enhance degradation by breaking down organic compounds to reduce the level of contaminants. These are broadly classified into aerobic and anaerobic treatments. Aerobic treatments rely on oxygen for oxidation reaction while anaerobic requires the presence of carbon dioxide for wastewater treatment. Conventionally aerobic digestion, aerated lagoons, activated sludge, oxidation ponds, and trickling filters are generally used for the effective treatment of waste (32). Sequential batch reactors (SBR) in activated sludge categories are more promising than others. Its efficiency depends upon dissolved oxygen rate, retention time, nutrient composition of wastewater, and others (52) However, managing air circulation in aerobic treatments becomes a challenging task (32). Although aerobic treatments possess sufficient removal efficiency of BOD, COD, and nutrients they require a large land area for set up also large-size reactors are generally used to acquire huge space (53). It also requires high energy as input for its aeration (53). Efficient functioning is limited because of the massive growth of microbes within the treatment process (32). Anaerobic treatment of dairy wastewater includes anaerobic digestion, anaerobic lagoons, up-flow anaerobic sludge blankets (UASB), anaerobic filter reactors, and others (52). UASB is generally suited for dairy waste containing low suspended solids due to its high efficiency regarding densely polluted wastewater (53,52). However, fats are one of the major problems in the efficient working of anaerobic treatment method because long-chain fatty acids forms layer on the surface and creates barrier for the assessment of anaerobic bacteria to organic matter (54,53).

However, conventional methods of physico-chemical and biological treatments are not very effective in terms of complete removal of microbial contaminants due to their resistant ability (29). Hence, a combination of biological techniques integrating with microbial-based treatments not only helps in the complete removal of contaminants but also generates value-added bio-based sustainable products that recycle their potential nutrients. Such a waste-to-wealth approach not only benefits the environment but also encourages economic opportunities and provides a boost to new industries. Hence, the researchers are focusing on finding innovative sustainable techniques to enhance the value of by-product and dairy waste by transforming it into bio-based products and providing a good alternative to conventional treatment strategies.

3. Microbial strategies for valorization of dairy waste: opportunity for transforming waste to wealth

Bio-based value-added products from dairy waste showcase the potential of sustainable ecology. Various new products can be formed by microbial techniques are discussed below and its detailed list is mentioned in (**Table 2**).

3.1 Biofertilizers

Dairy waste contains nutrient-rich elements like carbon, nitrogen, phosphorus, potassium, and other micronutrients which may sustain the microbes and can support soil fertility and enhance plant growth (55). Certain kinds of microbial metabolism can convert pollutants into plant-utilizable form hence, bio-fertilizer formulation for soil amendments can be made (45,55). Bio-fertilizers produced from different types of dairy waste water are given in (**Table 2**).

Six distinct bacteria of Firmicutes and Proteobacteria were isolated from the environment and mixed in the specific ratio were placed in a biofilm for microbial treatment which overall replaced 80% of the entire sections of effluent treatment plants such as storage and skimming tank, aerobic and anaerobic digester, sludge drying bed, settling and sludge tank which reduces the space requirement of convectional effluent treatment plant (56). Dairy processing sludge is also utilized as a biofertilizer as it contains nitrogen and phosphorus which support soil fertility and may

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replace chemical fertilizers (57). Literature also reveals that dairy sludge as a substrate can support the growth of Rhizobium by 60% hence, lowering the cost of biofertilizer (58)

Ammonia-rich liquid fertilizer was prepared by inoculating bacterial consortium of *Aeromonas*, *Acinetobacter*, and *Bacillus* of 66, 17 and 17% respectively in a biofilm reactor with a hydraulic retention time of 16hrs at ambient temperature yields bio-fertilizer containing 96.01 mg/l of ammonia, 73.72% nitrates and 72.46% phosphate within a biofilm reactor of processing capacity of 8064 m^3 per day with the flow rate of 360 L per hour. The biofertilizer enhanced grain yield in maize and biomass yield in sorghum and lemongrass by 1.19, 3.5, and 2.1 folds respectively (45).

3.2 Biofuel

Biofuel as a renewable source of energy derived from dairy waste provides a sustainable alternative to non-renewable fossil fuels contributing to waste management opportunities, lowering the emission of greenhouse gases, and reducing environmental impact (59). Microbial methods to enhance the conversion and utilization of nutrient-rich organic matter of dairy waste as a means to produce biofuel can be achieved by means of fermentation and hydrolysis (for bioethanol production) (60), lipid accumulation and trans-esterification (for biodiesel production) (61) and anaerobic digestion (for biogas production). Later on, the raw biofuels are upgraded, purified, or refined for clear separation of biofuel, meeting quality standards and enhancing its efficiency. Biofuels from different microbial strains like bacteria, fungi, and yeast can be produced from whey, sludge, expired, spoiled, milk residuals, or by-products of dairy waste depending upon the nature and types of feedstock composition, selection of microbial strains, processing efficiency, and economic feasibility. A detailed list of bio-fuel produced from dairy waste by using different microorganisms are given in (**Table 2**). Microbial-based conversion techniques provide opportunities to generate value-added bio-based energy sources from dairy waste. It not only provides environmental or economic benefits but also contributes in creating circular economy by reducing waste and energy dependence. Bio-fuel serves as an eye-catching valuable source for researchers and policymakers seeking the production of cost-effective biofuel and implements sustainable solutions for energy production as well as waste management.

3.2.1 Biogas production from dairy waste as a feedstock may be accomplished by a combination of technologies encompassing anaerobic digestion, co-digestion, or microbial inoculation. Anaerobic digestion is a key step of biogas production which involves the breaking down of organic constituents by the use of anaerobes producing methane and carbon dioxide along with traces of hydrogen sulfide and ammonia (62). The process involves hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Where *Bacillus, Acetivibrio*, and *Peptococcus* are known for hydrolysis (63), *Clostridium, Bacteroides*, and *Enterococcus spp.* are responsible for acidogenesis and *Methanobacterium* and archaea like *Methanoculleus*plays vital role in methanogenesis (64,65). Anaerobic digestion not only supports the removal of contaminants and generation of value-added products but it also creates renewable fuels substituting electricity and heat generation for wastewater treatment (66,67). Although Up-flow anaerobic sludge blankets (UASB) bioreactors have shown the highest COD removal. However, although bioreactor supports the growth of acidophiles but limits the growth of methanogens due to carbohydrate-rich dairy waste which may be overcome by the process of co-digestion (dairy waste combined with cattle dung, poultry, or livestock manure) (68,7). Hence, two-stage anaerobic digestion may be taken into account which separates acetogenesis and methanogenesis phase thus, improving biogas yield (69,7).An experiment was conducted where a blend of cheese whey and buttermilk was supplemented with 5% animal manure which resulted in the increase of hydrogen production in the initial phase till day 14 due to lactic acid bacteria specifically *Streptococcaceae* and *Lactobacillaceae* then on the later phase after day 14 there was simultaneous increase in clostridia and gradual decline in lactic acid bacteria (65). The research finding also suggests that anaerobic digestion of ultra-filtration permeates and di-filtration permeates could produce around 22,699 MWh of electricity and 85,516GJ of heat requiring 3MW biogas plant (70). Additionally, methane production efficiency ranged from 149 to 181NL/kg COD added (70).

3.2.2 Biohydrogen production from raw dairy effluent, cheese whey wastewater, and dairy sludge is the potential source of feedstock which on anaerobic digestion also releases methane along with hydrogen generation (71). Unlike the general hydrogen process, biohydrogen on combustion releases no greenhouse gases making it an alternative solution for hydrogen production from waste constituents. Dairy waste containing organic constituents is underused in terms of energy generation and production of cost-effective biohydrogen (72), however protein-rich dairy waste may hinder the growth of hydrogen-producing microorganisms, therefore to increase the efficiency of production different fermentation methods are being undertaken such as dark fermentation, continuous stirred tank reactor (CSTR) or Extended Sludge Bed Reactor (EGSBR) are used. In dark fermentation carbohydrates (lactose) in waste undergo hydrolysis by lactic acid bacteria to form lactate followed by anaerobic fermentation producing hydrogen. (73) In this process, a single unit of lactose produces 4.1 times biohydrogen by microbial consortium. (74) whereas in a continuous stirred tank reactor hydrogen production was estimated around 138.6 g lactose per liter per day with 2.8 mol hydrogen per mol lactose (75). Also, an extended sludge bed reactor (EGSBR) when employed for co-digestion with crude glycerol and cheese whey in a ratio of 5:1 produced a maximum yield of hydrogen (76,8). Other methods for biohydrogen production from cheese whey include microbial Electro Hydrogenesis Cells (MECs) under regulating pH and controlled conditions (77). Study results show Clostridium spp. as the best producer of biohydrogen from whey waste generating 3.65 mol of hydrogen per mol of lactose (78).

3.2.3 Bioethanol can be produced from the fermentation of lactose in the dairy bi-product or dairy wastes like whey, whey permeates, yoghurt, expired milk, etc. Researches reveal that microalgae can be a promising future in the production of biofuels. A study on *Arthospira platensis* suggests that it can be a potential source for bio-ethanol production (79). An experiment conducted on microalgal cultivation in dairy wastewater yields 16.35g/l biomass, COD removal was achieved by 95% and a further 14% ethanol was obtained from previously ultrasonicated microalgal biomass (80). Besides microalgae, yeasts like *Kluyveromyces marxianus* and *Kluyveromyces lactis* (81,82) and fungi like *Aspergillus oryzae* and *Neurospora intermedia* (83) can ferment lactose to ethanol directly or naturally. Hence, possessing an advantage over lignocellulosic feedstock and enhances the fermentation capacity which further increases ethanol production efficiency (84,85). *Kluyveromyces marxianus* produces 20g/l of ethanol from hydrolyzing lactose in dairy waste (86,87) whereas *Kluyveromyces fragilis* produces 81g/l of ethanol in 44 hrs from cheese whey powder when lactose concentration was 200g/l (88,44). A study examined how the initial substrate affects the rate of ethanol production; Whey powder and yeast as an initial substrate were used with initial pH value of 5 and oxidation-reduction potential value maintained at 250mV. The observation shows the conditions suited for the high rate of ethanol production were at initial sugar concentration below 75g/l and initial biomass above 850mg/l while avoiding substrate inhibition. However, ethanol production from dairy waste depends upon the nature and type of feedstock, characteristics of microbial strains, categories and composition of the substrate (89,90). Also, fermentation conditions like aeration rate, temperature, pH, agitation, and cell immobilization plays a crucial role during the production of ethanol (91,7).

3.2.4 Biodiesel production from dairy waste has been widely explored, and among all the different types of dairy waste, dairy scums have shown a viable result. Emphasizing triglycerides and free fatty acids can be precursors for transesterification reaction; biodiesel can be produced from plant, algal, and fungal biomass. Dairy sludge from the dairy industry as a feedstock also opens the way for cost-effective biodiesel production. Research findings from a lab study reveal that dairy sludge can generate around 14% of lipids, and from lipids, maximum biodiesel production was reported at 97%. Overall, 13% of biodiesel can be produced from dairy sludge (92). Another study reflects that biodiesel conversion by non-catalytic transesterification of dairy waste directly from dairy sludge (without any lipid extraction can be produced 32-39% by weight of dairy sludge at 380°c (93). An experiment was performed in which a rod-shaped oleaginous bacterium was able to accumulate lipids more than 80% of utilizing lactose, starch, sucrose, and glucose as a substrate, in addition to this, dairy wastewater was used as a sole source which produced 72% of lipid accumulation, producing biodiesel (94). Dairy effluent as a source of biodiesel production by solvent-based lipid extraction can produce 72% recovery when ethyl butyrate as a means of solvent extraction is used (95). Microalgal culture can be utilized for the treatment process of dairy wastewater and biodiesel generation as *Chlorella valgaris* inoculation in dairy effluent-produced biodiesel confirmed within ASTM standards (96). The study finding also highlights *Rhodhococcus opacus* resulted in 71% of lipid production from dairy wastewater when dextrose and ammonium nitrate were used as a source when dairy wastewater was used as a sole substrate resulting in 14.2% of lipid accumulation where this effect was enhanced to 32% when supplemented with 1:3 mineral salt media (97). Researchers also suggests that whey or whey permeate may be used for biodiesel production. One such study was conducted utilizing *Chlorella protothecoides* microalgae which are considered one of the best lipid-producing microalgae used for lipid production in dairy whey permeate utilizing glucose and galactose as a main carbon source resulted in biomass production of 9.1 g/L and 17.2g/L accumulating lipid to 42% and 20.5% when batch and fed batch culture were used respectively (98). *Mucor circinelloides* fungus and *Chlorella sorokiniana* microalgae may be used to enhance the lipid hydrolysis in dairy effluents or whey waste thus providing a means for the valorizing of dairy waste (99,100).

3.3 Bioplastics

Bioplastic is an environment-friendly polymer that serves the application in the food industry due to its physico-chemical attributes and non-polluting nature. More than 30% of bacteria synthesize polyhydroxyalkanoates (PHA’s) which are produced by genetically modified cultures or pure cultures (101). PHA’s majorly finds applications in food packaging due to their barrier characteristics and versatile nature (101). PHA’s are generally produced by utilizing lactose and lipid as a substrate of dairy waste; some microbes like *Bacillus megaterium*, *Thermus thermophillus*, and *Pseudomonas hydrogenovora* are able to directly convert lactose in dairy waste to bioplastics (91). Others use a combination of microbes to break down lactose into lactic acid or glucose and galactose which then produces PHA (102). Whey permeate as a feedstock is converted into PHA's during fermentation using a single or combination of different species of microbes like *Pseudomonas sp*., *Bacillus megaterium*, and *Brevibacterium casei* (44). Protein (casein) rich dairy waste is also considered a potential source for bioplastics manufacturing. A study was conducted in which among all other carbon sources, using buttermilk as a carbon source resulted in maximum biopolymer accumulation and this accumulation depends on remaining biomass (103). Although Protein (casein) rich dairy waste can form biopolymers but generates brittle films, other protein and polymer polysaccharides may be incorporated to produce better texture films or bioplastics (104). Also, the addition of gelatin, κ-carrageenan, and carboxymethyl cellulose also resulted in better textural properties and enhanced biodegradability (105). Some dairy waste is also used for the production of exopolysaccharides which are employed in improving texture, some strains like *Lactobacillus delbrueckii*, *Azetobacter chrococcum*, *Xanthomonas cucurbitae*, and *Pseudomonas* have the potential to produce exopolysaccharides (106,107).

3.4 Bioactive compounds

Bioactive peptides from dairy waste are produced as a result of protein hydrolysis by enzymes to produce bioactive peptides exhibiting diverse nutraceutical benefits and developing health-promoting functional food products (108). Milk-derived bioactive peptides have also shown immunodulatory effects, and control regulation of blood by ACE (Angiotensin Converting Enzyme) inhibition (109). Galacto-oligosaccharides production from dairy whey not only supports probiotics but also enhances nutritional value (110). In a study, microalgae *Tetradesmus obliquus* was able to produce galacto-oligosaccharides from whey permeate by enzymatic catalyst (111). Bioactive compounds were obtained by using algal strains of *Porphyridium purpureum* as a culture in cheese whey which resulted in the production of exopolysaccharides by consuming lactose present in the whey (112). Recent technologies employed for the extraction of bioactive compounds are enzymatic hydrolysis or fermentation technique which may also be used in combination with novel techniques like membrane separation, high pressure, ultrasound, pulse electric field, or microwave assisted (113,114). In a study, a peptide fraction of 3.5ml was extracted from scotta (waste of ricotta cheese) by ultrafiltration (115). Pomiferin was extracted from the fruit of *Maclura pimifera*and was able to clot milk similar to chymosin, antioxidant and ACE inhibition in whey obtained was 57.4 and 11% respectively (116).

3.5 Dairy waste as a source of single-cell proteins

Single-cell proteins are protein-rich edible components produced by drying and processing of the cell of microorganisms like bacteria, yeast, moulds, or fungi that are GRAS (Generally Recognized as Safe) are used as food and feed for supporting the nutritional requirement of protein in humans or animals (117). Dairy waste containing good sources of lactose, protein, and minerals can be utilized as a substrate for the production of single-cell protein (118). A study was conducted using *Saccharomyces cerevisiae* and *Lactobacillus acidophilus* as an inoculum in dairy wastewater treatment for 7 days of incubation resulting in biomass yield of 0.32 and 0.16g/L for each microorganism respectively (118). Some microorganisms employed for single-cell protein are *Fusarium, Trichnoderma, Candida, Saccharomyces, Chlorella, Kluyveromyces, Aspergillus, Rhizopus, Neurospora, Monascus*, and others producing around 40-70% of yield (118, 119,120,121). In a research *Kluyveromyces lactis* and *Rhodotorula graminis* were selected to generate single-cell protein from milk waste in which a combined consortium of this yeast resulted in an impressive yield of 44g/L of dry cell weight (122). Similarly, in another study on using whey as a substrate for growing single-cell protein by mixed consortia of *Kluyveromyces marxianus* and *Candida krusei* at a high temperature of 40°c and low pH 3.5 in aerobic fermentation produced better quality single-cell protein yield of 43.3% protein (123). An experiment also reveals tofu waste and cheese whey waste can be sources of single-cell protein cultivation medium by *Chlorella* spp. inoculums (124). However, a major limitation in single-cell protein production is the generation of high amounts of nucleic acids which are harmful for animal consumption, a prerequisite of nucleic acid removal should be effectively performed before the production of single-cell protein (125).

3.6 Biosurfactants

Biosurfactants are the surface-active compounds (consisting of hydrophobic and hydrophilic components) produced by microorganisms which are known to reduce the surface tension of liquids and are the best alternative to chemical surfactants (126,127). Also, they are non-toxic, biodegradable, and more stable in harsh environments (128). This offers a wide range of applications in the food industry, wastewater treatment, pharmaceuticals, agriculture, and environmental remediation (129,130). In food product, it may be used in improving texture, enhancing stability, emulsion, detergent, solubilization dispersion of flavors and colors, and many others (131). *Pseudomonas spp*. and *Bacillus subtilis* are the most promising and widely used microbes in biosurfactant production (132). The strain of *Pseudomonas aeruginosa* was used as feedstock in whey waste producing secondary metabolites after fermentation biosurfactant containing surface active properties was recovered, also reduction in COD of whey waste was 87% and there was a signification reduction in phosphate, nitrogen, and total acid content (133). A similar study was conducted on cheese whey using *Pseudomonas aeruginosa* for the production of rhamnolipids biosurfactant yielding 2.7g/L and 4.8g/L when supplemented with 2% glucose and mineral salt (134). A researcher utilized whey waste for biosurfactant production using *Streptococcus thermophilus*, *Lactobacillus acidophilus*, and *Lactobacillus rhamnosus*, then characteristics like emulsification index, surface tension, oil spreading, anti-adhesion properties and biomass of obtained biosurfactant were studied (135). *Bacillus methylotrophicus* and *Bacillus pumilus* were cultured on whey permeate by ultrafiltration and biosurfactant was produced and later purified and characterized (136).

3.7 Microbial Fuel Cells

Microbial Fuel Cells are one of the sustainable electrochemical systems that use microorganisms to produce bioelectricity (33). Certain microbes such as algae or lactose fermenting bacteria feed on the organic matter harnessing dairy waste and produce electrons and protons as by-products hence generating electric current (44). In an experiment *Shewanella alga as a biocatalyst was* used in treating dairy wastewater and power generation which resulted in 92.21% of COD removal and generated 666 mV after 286 hours of incubation (137). Similarly, *Escherichia coli*-K-12 as a biocatalyst in dairy waste generated 654mV current with 67.5% coulombic efficiency after 123hrs of incubation (138). Phytochemicals from *Amaranthus blitum* plant species were extracted and used as a means of power generation using dairy effluent utilizing cu-doped FeO nanoparticles for generating electrical energy providing an alternative and renewable source of energy (139). Mixed consortia of *Shewanella oneidensis* and *Clostridium butyricum* were inoculated in a bioreactor containing dairy wastewater as a substrate generating a power density of 2.4W/m to 3.5W/m and a current density of 1.1 A/m to 2.4A/m and columbic efficiency of 2.1- 4.4% in two different phases (140). 27W/m^3 power density resulted when using a feed of industrial dairy wastewater for 2.5 months of operation (141). Utilization of cheese whey can also offer a novel approach towards power generation as lactose in whey can fuel a power density of 1839µW/cm^2 (142) also, yeast like *Saccharomyces cerevisiae* PTCC 5269 consumes sugar from whey waste and generates highest electric current of 50µW and 470µA of constant voltage for 2 days (142). Microbes like *Lactobacillus bulgaricus*, *Streptococcus thermophilus*, and *Lactobacillus casei* can also be used as an inoculant in cheese whey to generate power (143). One of the challenging tasks in microbial fuel cells is maintaining stability in electricity production, as in batch mode, bacteria feed on substrate produces higher voltage initially which diminishes thereafter resulting in inconsistent voltage supply, to overcome this fed-batch system may be implemented for constant voltage supply throughout. Hence providing sustainable solutions and enhancing the valorization of dairy waste (138,144)

3.8 Dairy waste for the production of organic acids

Organic acids are the high value-added compounds synthesized by biochemical processes carried out by microbial fermentation under suitable conditions (145). Advancements in the bioprocessing technologies for organic acid production have efficiently utilized the resource potential of dairy waste by producing valuable compounds that can be used in various industries like pharmaceutical, agricultural, polymer, food, and beverages industries (146,147). A detailed list of organic acids produced from dairy waste are given in (**Table 2**). Some common organic acids produced by utilizing dairy waste are lactic acid, citric acid, succinic acids, and acetic acids depending on dairy waste composition, types of microbial strains and their adaptations, fermentation conditions, and oxygen availability (148,149).

3.8.1 Lactic acid is used as a preservative and flavoring agent in many food industries (150). For example, *Lacto bulgaricus* GCMCC 1.6970 was utilized for cost-effective D-lactic acid production from cheese whey powder in batch fermentation and fed-batch fermentation yielding 70.70g/L and 113.18g/L respectively, additionally, proteases enzymes were used for complete hydrolysis of protein and efficient production of D-lactic acid (151). *Lactobacillus delbrueckii*, *Lactobacillus casei*, *Lactobacillus helviticus*, *Lactobacillus plantarum*, and *Lactobacillus rhamnosus* are also of great potential in producing lactic acid from dairy waste (152,153,154). A study conducted on dairy waste supplemented with glucose for better yield resulted in 14.2g/L production of lactic acid along with 0.78g/g sugar within 41.41 hours of fermentation with productivity of 0.34g/L/h (155). When mixed milk whey and ricotta cheese whey were used as a medium for fermenting lactic acid by *Lactobacillus casei* resulted in the highest production of 78.3% within 60hr, also the research finding reported no toxicity in using *lactobacillus* spp. in lactic acid fermentation (156).

3.8.2 Citric acids are fermented utilizing dairy waste contributing to waste valorization, for instance among yeast, *Yarrowia lipolytica*, and among fungi, *Aspergillus niger*is considered most promising in the production of citric acid from dairy waste (157,158). To enhance the production dairy waste may be supplemented with sugar like glucose, fructose, and galactose (159,160). Research reported whey supplemented with 15% sucrose produces the highest amount of 106.5g/L of citric acid production (160). And with supplementation of calcium alginate, *Aspergillus niger* resulted in a 70.3% yield with productivity of 160mg/L/h (161). A recent study on the citric acid production from deproteinized cheese whey using *Yarrowia lipolytica* B9 shows optimum conditions for efficient production is a temperature of around 20°c and pH 5.5 yielding 33.3g/L concentration (162).

3.8.3 Propionic acid production from dairy or cheese waste are majorly reported by strains of *Propionibacterium acidipropionici* and *Propionibacterium freudenreichii* (163) in which highest propionic acid production was reported in pure whey lactose as a substrate resulting 22.57h/L when supplemented with pure and crude glycerol the yield increased to 24.47g/L and 24.80g/L respectively (164). Used whey was applied to produce propionic acid and preserve vitamin B12 production (165). A recent study also highlights *Propionibacterium cyclohexanicum*, *Acidipropionibacterium jenesenii*, *Acidipropionibacterium thoenii*, *Acidipropionibacterium acidipropionici* have the ability to produce organic acid by utilizing lactose as a substrate in dairy waste (166). Acetic acid, propionic acid, and succinic acid were jointly produced in different ratios at a fermenting temperature of 35°c and initial pH of 6.5 using *Propionibacterium acidipropionici*as a culture with using a mixture of 3 different effluents like whey, corn steep liquor, and effluent from animal feed production (167).

3.8.4 Succinic acid production was reported using whey and lactose with *Acinobacillus succinogenes* 130Z as an inoculum in a batch fermentation method yielding 62.1% and 65% with production of succinic acid with 35g/L of whey and 25g/L of lactose from dairy waste (168). The same strain reported 24.9g/L production of succinic acid from cheese whey by batch fermentation (169)

3.9 Dairy waste as producing enzymes for multifarious applications

Enzyme production from dairy waste is a sustainable approach to reducing environmental concerns of waste disposal (170). Enzyme production from dairy waste also supports the growing demand for industrial enzymes (171). These enzymes viz., proteases, amylases, lipases, β-galactosidases, α-galactosidases, and α-amylases have been used across varied applications such as in bioremediation, biofuel production, detergent making, food processing, polymer production, biosensors, and agricultural industries (172,173). Enzyme production from dairy waste may vary depending on substrate composition and concentration, microbial strains and contamination issues, temperature and pH, fermentation conditions, and techniques (174). These enzymes are produced cost-effectively by using dairy waste as a substrate for enzyme extraction. Strains like *Aspergillus niger*, *Pseudomonas spp*., *Streptococcus spp*., *Lactobacillus spp*., have the ability to produce enzymes from dairy waste (175). Moreover, enzyme production from dairy waste not only helps in reducing pollutants but also frames a sustainable approach in value-addition.β-galactosidase action on dairy waste catalyzes trans-galactosylation forming a combination of oligosaccharides (11). Fungi like *Kluveromyces lactis*, *Aspergillus oryzae*, *Mucor spp*., and bacteria like *Paracoccus marcusii,* and *Bifidobacteriumbifidum* are identified for the production of β-galactosidases from lactose rich dairy waste like whey (7,11).

Table 2: List of some bio-based products from dairy waste

Bio-product	Waste	Processes	Microbial strains	Product obtained	Production yield	References
Biofertilizer	Dairy waste water	Bioreactor fermentation	*Aeromonas, Acinobacter and Bacillus*	Ammonia rich bio-fertilizer	96.01mg/L ammonia	(45)
	Whey	Fermentation	*Lactobacillis rhamonsus*	Soil biostimulants product	----	(176)
Biofuel	Dairy wastewater	Anaerobic digestion	*Penicillium citrinum*	Biogas (Methane)	231mL/g Volatile Solids	(24)
	Cheese whey + Wastewater	Dark fermentation	*Clostridium beijerinckii*	Biohydrogen	833.1 ml/L/d	(177)
	Dairy wastewater	Fermentation	*Arthrospira platensis*	Bioethanol	---	(79)
	Cheese whey powder	Batch fermentation	*Kluyveromyces marxianus*	Bioethanol	34.8g/L at 109g/L initial lactose concentration	(90)
	Dairy effluent	Transesterification	*Yarrowia lipolytica*	Biodiesel	61%	(178)
Bioplastics	Cheese whey	Fermentation	Halomonas alkaliantarctica	Bioplastics (PHA)	0.42g/L	(179)
	Whey	Fermentation	Ralstonia eutropha	Bioplastics (PHB)	4.71g/L	(180)
Bioactive compound	Cheese whey	Batch fermentation	Kluyveromyces lactis	Galactooligosaccharides (GOS)	63.2%	(181)
	Acid whey	Batch fermentation	Lactococcus lactis	Nisin	$2.6*10^5$ AU/ml	(182)

	Whey Protein Concentrate (WPC)	Fermentation	*Lactobacillus fermentum* and *sacharomyces cerevisiae*	Bioactive peptide	7.24mg/ml (*L. fermentum*) and 8.59mg/ml (*S. cerevisiae*)	(183)
Single-cell protein	Milk waste	Fermentation	*Kluyveromyces lactis* and *Rhodotorula graminis*	Single-cell protein	44g/L of dry cell weight	(122)
Biosurfactant	Paneer whey	Fermentation and Emulsification	*Pseudomonas aeruginosa*	Biosurfactant	2.7g/L	(134)
	Cheese whey permeate	Fermentation	*Lactobacillus* strains	Biosurfactant	Max reduction by *Limosilactobacillus fermentum* 34.9 mN/m	(184)
	Paneer whey		*Bacillus licheniformis*	Biosurfactant	3.3g/L	(185)
Microbial fuel cell	Dairy waste Water	Batch process	*Pseudomonas aeruginosa*	Bioelectricity	161 mA/m^2current density and 34.82 mW/m^2 Power density	(137)
	Dairy wastewater	Fermentation	*Shewanella oneidensis* and *Clostridium butyricum*	Bioelectricity	2.4W/m to 3.5W/m Power density and 1.1A/m to 2.4A/m Current density	(140)
Organic acids	Milk whey and cheese whey	Fermentation	*Lactobacillus casei*	Lactic acid	78.3%	(150)
	Cheese whey	Fermentation	*Yarrowia lipolytica*	Citric acid	33.3g/L	(162)
	Dairy waste	Fermentation	*PropionibacteriumAcidopropionici* and *Propionibacterium freudenreichii*	Propionic acid	22.57 h/L	(163)
	Cheese whey	Batch fermentation	Acinobacillus	Succinic acid	24.9 g/L	(169)
Enzymes	Dairy waste		Chlamydomonas reinhardtii	β-glucosidase	0.18mg/L	(6)

4. Conclusion :

As dairy industries are expanding to meet huge demands of dairy products, dairy industries tend to generate a huge amount of waste polluting the environment and harming the ecosystem, Hence, valorization of dairy waste offers a great opportunity for reducing environmental pollution, generating renewable energy, resource recovery, innovating valuable commodities, enhancing sustainability, and promoting circular economy. The bio-based product obtained from dairy waste has applications in various industries like pharmaceuticals, nutraceuticals, biopolymers, food processing, and agriculture. Hence, creating opportunities for research and advancements in the field of waste management and formulating value-added products. However, there are some limitations in valorizing the full potential of dairy waste (1) Maintenance and operation of large-scale operations for anaerobic digestion, fermentation, or enzymatic hydrolysis on a large scale can be technically challenging, hence specific research needs to be done for process optimization. (2) Energy-intensive operations may cut down the environmental issues but increase the overall economic viability. (3) Dairy waste is a complex mixture of different components that may affect processes like inhibition of microbial activity due to high concentrations of fat, protein, and lactose or may sometimes be unable to match the nutritional requirements of microbes for carbon to nitrogen ratio. (4) Insufficient infrastructure, low capital budget, and uncertain market demand for specific products may affect the proper utilization and conversion of dairy waste into valuable bio-based products. A multidisciplinary research approach may help in the efficient utilization and implementation of waste management strategies.

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