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Sustainable Strategies for the Dairy Industry Waste Management and Repurposing

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The global dairy sector experiences significant growth due to rising demand, but faces environmental concerns from harmful waste discharge, endangering ecosystems and human health. Dairy waste, emitting 4-11 million tons annually, threatens biodiversity and aquatic oxygen levels. Biological methods, cost-effective and efficient in removing chemical demand, are preferred for treatment. Research suggests dairy by-products can be repurposed for industrial use or energy generation, offering solutions to pollution. Biotechnological approaches present promising alternatives for reducing organic loads, highlighting the need for comprehensive management practices.

Types of waste are generated during the processing of dairy products

The dairy industry's effluent is a significant environmental concern, these wastes stem from milk fermentation and processing by-products, potentially repurposable for other dairy products like whey concentrates, dairy sludges and waste water. Typically containing suspended solids, organic matter, nitrogen, phosphorus, and oil/grease, they may also harbor residues from cleaning agents. With burgeoning global demand for dairy, waste generation escalates due to intensive processing, heavily reliant on water. This usage spans all production stages, leading to increased discharge. In dairy operations, the processing, cleaning, and sanitary wastewater categories collectively generate wastewater about 6-10 liters for every liter of processed milk. (Britz, van Schalkwyk, & Hung, 2006).

Characteristics and composition of dairy industrial waste

Dairy wastewater, rich in organic compounds, oil, grease, and nutrients like casein and lactose, varies depending on production methods. By-products such as whey are rich in lipids, carbohydrates, vitamins, and minerals. The wastewater, with high COD and BOD levels, appears white with a disagreeable odor and is turbid. Parameters like BOD, COD, TSS, nitrogen, and phosphorus are crucial, with effluent characteristics varying among different dairy industries.

Dairy industrial effluents pose harmful environmental effects

Dairy farming effluents, nutrient-rich, strain sewage, harming air, soil, and water, disrupting climate patterns and degrading water quality, promoting diseases like malaria. Waste obstructs treatment, lowers oxygen, poses health risks to groundwater due to nitrogen compounds. Whey contributes to soil and water pollution, harming aquatic life and ecosystems. Urgent measures needed to mitigate wastewater discharge and prevent further environmental damage. Utilization and treatment, including wetland treatment, are crucial.

Utilization and treatment of dairy waste

Wetland treatment

For decades, developed nations relied on expensive centralized wastewater treatment facilities, posing financial and environmental challenges. Meanwhile, developing countries lacked resources for such systems, leading to untreated wastewater discharge. Wetlands emerged as a sustainable, cost-efficient alternative, utilizing natural processes to purify wastewater, especially suitable for dairy effluents due to their simplicity and lack of sludge recycling. Benefits include lower costs, simpler infrastructure, and longer lifespan, although drawbacks include larger surface area requirements and potential groundwater risks. Despite challenges, wetlands have proven effective in treating dairy wastewater in various countries, reducing biochemical oxygen demand levels significantly.

Physico-chemical treatment

Physico-chemical treatments, including coagulation, are vital for addressing milk fat and protein colloids in dairy wastewater, reducing suspended particles, turbidity, COD, and BOD levels. Coagulant addition destabilizes particulate matter, aiding in floc formation for flotation or sedimentation; natural coagulation via lactic acid bacteria fermentation can also be enhanced with chitosan or CMC for significant COD reduction. Further treatment with powdered activated charcoal removes color and odor, while oxidation pretreatment with FeSO4 and H2O2 can remove up to 80% of fat from cheese wastewater, offering a promising approach for efficient waste management.

Biological treatment

Biological treatment methods such as trickling filters and activated sludge are widely favored for managing dairy wastewater, effectively removing organic matter, although they may produce problematic sludge. Despite challenges, these systems have the capability to break down complex organics and adsorb heavy metals. Within biological treatment, aerobic and anaerobic methods are distinguished, with aerobic methods being prevalent in dairy wastewater treatment plants, despite facing issues like rapid acidification and filamentous growth, leading to reduced efficiency Notably, aerobic bacteria exhibit lesser effectiveness than anaerobic bacteria, particularly in phosphorus removal. Sequencing batch reactors (SBR) are favored in dairy wastewater treatment due to their adaptable loading capacities and efficient management. The Intermittently Aerated Sequencing Batch Reactor (IASBR) technology has emerged to address nutrient remediation constraints, offering enhanced nutrient removal efficiency with lower energy and infrastructure demands.

Biotechnological methods in dairy industry waste

Utilizing biotechnological processes such as aerobic and anaerobic microbial fermentation, anaerobic digestion, and fuel cells enables bioconversion. Furthermore, the combination of biotechnological and physiochemical methods can produce value-added products.

Biomass production

Researchers utilized *Acutodesmus dimorphus* cells to treat raw dairy wastewater, achieving >90% COD reduction in 4 days and complete ammoniacal nitrogen consumption in 6 days. Biomass analysis showed 25% lipids and 30% carbohydrates, suggesting potential for biodiesel and bioethanol conversion, aiding sustainable wastewater disposal. Another study explored the use of a 20:80 mixture of olive oil press waste and milk whey as a substrate for *Geotrichum candidum* growth. Successful cultivation for 5 days at 30°C under anaerobic conditions highlighted its potential as a cost-effective and efficient substrate for biomass production, without requiring water dilution or extra nutrients.

Bioplastics

Biodegradable materials like polyhydroxyalkanoates (PHA) offer a greener alternative to oil-based plastics, reducing pollution. Research by Pakalapati et al. (2018) highlights PHA's potential from whey. Marangoni et al. (2002) demonstrated successful PHA production from whey permeate, with a commercially appealing 38% 3HV composition. Pandian et al. (2010) showcased efficient PHB production from dairy waste by *Bacillus megaterium* SRKP-3. Additionally, *Brevibacterium casei* SRKP2 and *Pseudomonas hydrogenovora* show promise in PHB production from industrial waste, holding potential for diverse applications like drug delivery (Pandian et al., 2010).

Biofertilizer

The research revealed that dairy industry sludge, when utilized as a growth medium, significantly enhances the rapid growth of rhizobia. Results demonstrated that incorporating 60% dairy sludge into the medium outperformed the traditional medium for Rhizobium, known as Yeast Extract Mannitol Broth. Thus, the study proposes that integrating dairy sludge as a substrate could substantially reduce the production costs of bio fertilizers.

Biofuels

The dairy industry produces effective sludge used in diverse applications. Biofuels derived from dairy waste offer eco-friendly alternatives to fossil fuels, emitting fewer pollutants. The dairy industry's sludge serves diverse purposes. Biofuels from dairy waste offer eco-friendly options, emitting fewer pollutants. Yeast strains like *Kluyveromyces fragilis* convert waste into ethanol. Optimization studies maximize ethanol production through fermentation. Immobilized *Candida inconspicua* W16 yields high ethanol from whey, cutting costs.

Single Cell Protein

Single-cell proteins (SCP), comprising 40-80% of dried weight as crude protein, mimic animal proteins, ensuring high quality. GRAS microorganisms, notably yeasts like *Kluyveromyces* and *Candida*, are preferred for SCP production due to cost-effectiveness and lactose metabolism. *Kluyveromyces marxianus* stands out for commercial efficiency. Microorganism selection hinges on lactose metabolism for biomass production. Optimal growth requires simple nitrogen sources and temperatures around 25-35°C for yeasts and 30°C for bacteria, with thermophilic strains thriving at higher temperatures.

Organic acid production

Chemical compounds play crucial roles in enhancing flavor, stability, and preservation in food, beverage, and pharmaceutical industries, sourced notably from milk whey. Citric acid production utilizing *Aspergillus niger* ATCC 9642 from milk whey, shows surface fermentation methods' superiority over submerged ones, offering heightened yield and lower process sensitivity. Sustainable bioprocesses such as succinic acid production with *Actinobacillus succinogenes* 130Z and lactic acid extraction via *Lactobacillus casei* ATCC393 from yogurt whey yield value-added products. *Propionibacterium*-driven propionic acid production underscores milk whey's potential for preservative and probiotic applications, showcasing the versatility and sustainability of these bioprocesses in various industries.

Bioactive peptides

Bioactive peptides, derived from precursor proteins through enzymatic or chemical hydrolysis, exhibit various biological activities. The enzymes involved and the conditions for peptide release depend on the source protein. These peptides, due to their structure facilitating rapid absorption and timely utilization, hold promise as nutritional supplements for human consumption. Primary sources include milk, whey, and colostrum. Recent research demonstrates the feasibility of obtaining bioactive compounds through biotechnological methods. For instance, a study extracted pomiferin from the latex of *Maclura pomifera* fruits, which proved effective as a milk clotting agent, potentially replacing chymosin. Bioactive peptides, generated from chymosin, endowed the resulting whey with antihypertensive and antioxidant properties. Consequently, the modified whey could serve as a valuable ingredient in functional foods, offering potential benefits for both consumers and the food industry.

Polysaccharides

Whey, a cheese production byproduct, is crucial for polysaccharide production like xanthan gum and exopolysaccharides (EPS). Xanthan gum, synthesized from whey lactose via fermentation with *Xanthomonas campestris*, and EPS, including dextrans, produced with *Leuconostoc mesenteroides*, play vital roles in adhesion, biofilm formation, and environmental protection. They offer diverse functional properties applicable in food and pharmaceutical industries, including viscosity modification, emulsification, texture enhancement, detoxification, stabilization, and anti-neoplastic effects. Optimal EPS production, reaching 152 mg L^{-1}, is achieved through fermentation with deproteinized whey and yeast extract, employing *Streptococcus thermophilus* SY at pH 6.4, 36°C for 12 hours.

Biosurfactants

Biosurfactants (BS) are versatile, used in agriculture, pharmaceuticals, cosmetics, and food for their surface tension-lowering abilities. *Candida bombicola* ATCC 22214 efficiently produces sophorolipids (SLs) from synthetic dairy wastewater, using cost-effective sources like sugarcane molasses and soybean oil. Commercial feasibility versus petrochemical surfactants relies on cost and production capacity, though eco-friendliness offers competitive advantages in specialty markets. Prioritized research should optimize production processes, microorganisms, substrates, and downstream processing for competitiveness. *Bacillus* *licheniformis* M104 produces antimicrobial BS lipopeptides from milk whey, addressing dairy wastewater challenges for sustainability and valuable bioproducts.

Conclusion

The dairy industry, a key player in food processing, consumes vast water amounts and produces significant dairy effluent. This waste varies in composition, often containing high organics, BOD, COD, and temperature. Improper disposal can harm the environment, affecting aquatic life, agriculture, and human health. However, dairy by-products can be transformed into valuable chemicals, aiding sectors like food, fuel, health, pharmaceuticals, and plastics, thereby reducing pollution and mitigating environmental damage. Further research is needed to optimize these processes for cost-effective and practical solutions.

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