CHILEAN JOURNAL
of AGRICULTURAL RESEARCH

CHILEANJAR
CHILEAN JOURNAL of AGRICULTURAL RESEARCH

REVIEW

Advanced sustainable practices: Exploring alternatives for wastewater reuse and nutrient recovery from animal production effluents, a review

Olga Herrera[1] **and Johannes de Bruijn**[1, 2*]

[1]Universidad de Concepción, Facultad de Ingeniería Agrícola, Chillán, Chile.
[2]Universidad de Concepción, Centro de Desarrollo Tecnológico Agroindustrial, Los Ángeles, Chile.
[*]Corresponding author (jdebruij@udec.cl).
Received: 9 July 2024; Accepted: 3 September 2024, doi:10.4067/S0718-58392025000100147

ABSTRACT

Water is a vital resource for human survival, being the center of sustainable development. On the other hand, the livestock sector emerges as a major water consumer, producing a substantial volume of nutrient-rich wastewater. Consequently, the feasibility of reusing wastewater and recovering its nutrients becomes necessary to promote the sustainability of water sources. The aim of this study was to generate knowledge about tertiary treatment of wastewater from livestock and poultry industry, the reutilization of water and recovery of its nutrients, and potential applications. A systematic literature review by searching ScienceDirect and Web of Science platforms provides an exploration of technologies that facilitate the reuse of water and recovery of nutrients from livestock and poultry wastewater, including membrane filtration. As a result, the concentrated waste stream from membrane filtration can be utilized by an additional treatment of microalgae, bacteria or synergic consortia of microalgae and bacteria, in particular lactic acid bacteria that are innocuous to humans. Finally, the integration of these technologies presents a promising way to produce valuable biotechnological products with versatile applications in the pharmaceutical and food industries. However, the implementation of these technologies on an industrial scale requires more research.

Key words: Livestock, poultry, waste valorization, wastewater, water reutilization.

INTRODUCTION

Water, as the cornerstone of life and a vital resource of human activities, remains the most precious among our natural assets (Unfried et al., 2022). Currently, factors such as population growth, urbanization, and economic development are exerting significant pressure on available water resources, which affect water quality and availability (Lee and Jepson, 2020; Unfried et al., 2022). Reuse of water stands as a valuable tool for wastewater valorization by its potential reincorporation in domestic, industrial, and agricultural sectors. Among the emerging paradigms, the circular economy (CE) framework has gained prominence (Åkerman et al., 2020; Robles et al., 2020). This approach encourages a transformative shift from traditional linear take-make-use-disposal systems to more sustainable take-make-use-reuse systems, thus facilitating the transition to a sustainable society (Åkerman et al., 2020). Livestock and poultry sectors, as significant water consumers, mean a special challenge for wastewater treatment within the CE paradigm (López-Sánchez et al., 2022; Vaishnav et al., 2023). This challenge arises due to the intricate combination of animal and chemical residues, elevated nutrient concentrations, microorganisms, and pollutants inherent to livestock and poultry effluents. Depending on specific applications, the imperative of wastewater treatment becomes evident to ensure the required water quality, adopting non-conventional systems, either alone or in combination, to facilitate water reuse and nutrient recovery (Thapa et al., 2022; Yaashikaa et al., 2022; Khanal et al., 2023). Elevating wastewater quality by tertiary treatments yields water suitable for applications in irrigation or reintegration into the production process. Simultaneously, valuable compounds can be recovered and subsequently transformed into products, such as biogas and biohydrogen (Sarawaneeyaruk et al., 2019; Chen et al., 2020; Niquice-Janeiro et al., 2020; Manasfi et al., 2021). This paradigm agrees with the principles of CE providing respect for ecological limits (Patwa et al., 2021). This study aimed to determine worldwide trends in tertiary treatment of wastewater from the livestock and poultry industry, the reutilization of water and the recovery of its nutrients, including their potential applications, over the last seven years (2018-2024).

LIVESTOCK AND POULTRY WASTEWATER CHARACTERISTICS

The production of wastewater can be an important source of water pollution if it is not treated, as it contains large amounts of organic matter, nutrients, pathogens and pharmaceutical compounds (Vaishnav et al., 2023). Another problem is the contamination of groundwater, which can be polluted by livestock effluent as it percolates through the soil. Wastewater can be classified according to its source, which is described below.

Cattle wastewater

The cattle population was approximately 1.6 billion heads in 2018 worldwide, producing 37 kg wastewater per head per year (Shen et al., 2018). In addition to the large volume of wastewater produced, the picture is rather complicated due to its wide pH range, high temperature, high organic load, high total soluble solids (TSS) and chemical oxygen demand (COD) (Table 1). De Matos Nascimento et al. (2020) assessed the composition of bovine wastewater in order to understand the impact of this effluent on the environment.

Table 1. Values of water quality parameters found in livestock and poultry wastewater. TN: Total N; TP: total P; NH_3-N: ammoniacal N; COD: chemical oxygen demand.

Type of wastewater	pH	TN	TP	NH_3-N	COD	References
		mg L^{-1}				
Cattle	7.1-8.1	95-1230	41-86	498-660	2900-10400	de Mendonça et al., 2018; Lv et al., 2018; Daneshvar et al., 2019
Poultry	7.1-7.3	49-80	7.5-55	123-150	350-4000	Ferreira et al., 2018; Hülsen et al., 2018; Zheng et al., 2019; Artukmetov et al., 2021
Swine	6.4-6.8	200-2050	100-620	110-1600	2000-37000	Cheng et al., 2019; López-Pacheco et al., 2019; Oliveira et al., 2020

Poultry wastewater

The broiler population was estimated in 66.5 billion in 2020 worldwide, where almost 26.5 L of water were required for producing one broiler (Goswami and Pugazhenthi, 2020). Its wastewater is a major source of water pollution, like previous effluent, it contains organic matter and nutrients (Artukmetov et al., 2021). It is mainly composed of feces, feathers, feed debris and water. It also contains fats, proteins, suspended solids, macronutrients such as N, P and K, thus the greatest danger of this wastewater for the environment is related to the eutrophication of water ponds. On the other hand, these concentrations can vary according to the type of poultry, the amount of feces and management practices (Oueslati et al., 2021). Table 1 shows concentration ranges of water quality parameters according to literature.

Swine wastewater

Pork is the second most consumed meat in the world, corresponding to 118.8 million tons in 2018 (Tsai, 2018; FAO, 2021). The production of 770 billion of pigs worldwide in 2018 with 4-8 L of effluent per animal per day generates a huge amount of wastewater (Tsai, 2018; Vaishnav et al., 2023). The composition of this wastewater varies according to the production system, the physiology of the animals and the management procedures performed on the farms. The effluent generated contains high levels of organic matter, including urine, feed residues, feed wastewater, farm cleaning water and other compounds such as hormones and antibiotics, with about 10% of solids (Zhang et al., 2018; Cheng et al., 2020a). In the case of feces, they contain P, Cu, Zn and N (particularly ammonia) because these nutrients are incorporated into their diet to improve feed efficiency and overall health (Zhou et al., 2019). According to Table 1 swine wastewater contains the highest concentrations of pollutants; therefore, a suitable treatment is required.

PHYSICAL AND CHEMICAL TREATMENTS

To produce 200 kg of meat, the livestock sector consumes 15 000 L of water, resulting in the generation of substantial slurry amounts with abundant recoverable nutrients (Xie et al., 2020). About 3000 L of slurry are generated per animal annually, including the bovine, swine, and poultry segments. Constituting primarily of feces, urine, feed rests, and cleansing effluents from animal facilities, these residues exhibit variability due to species, age, feed composition, and rearing conditions (Nagarajan et al., 2020; López-Sánchez et al., 2022). Owing to their composition, key indicators of wastewater quality such as chemical oxygen demand (COD), total N (TN), total P (TP), ammoniacal N (NH_3-N), and pH require monitoring to preclude detrimental environmental consequences (López-Sánchez et al., 2022).

Wastewater, an invaluable reservoir of water, possesses the potential to yield nutrients and energy. However, to manage wastewaters according to the concept of circular economy, changes must be introduced in current treatment systems, including the reuse of livestock slurry. The feasibility to apply such treatments depends on factors such as the material flux to be treated and the content of organic matter in the effluent.

There are several physical and chemical technologies for water reuse and waste recovery, including advanced oxidation processes (Table 2). Applying electrocoagulation, for example, to poultry wastewater, water recovery varies between 50%-75% with a sludge recovery of 5%-10% (Vaishnav et al., 2023). However, there are several parameters such as maintenance costs, as well as the performance of these technologies, which are a disadvantage for their implementation (Table 2). In order to scale up these technologies, several aspects must be considered in order to improve them. Research work is underway, but more analysis must be done regarding process costs, toxicity of effluents and by-products, catalyst technology and reactor design, among others (Domingues et al., 2021). According to Table 2, the treatment alternatives are effective in terms of organic matter degradation, reaction speed and operating conditions. Reused water is a hydrologically independent year-round source that can buffer the impacts of water scarcity (Lee and Jepson, 2020). One of the advantages of water reuse is the possibility of reducing the pressure of water consumption and, on the other hand, allowing to valorize the waste present in such water by various technologies, which are rapidly expanding due to the need to properly recycle some key elements of wastewater (such as N and P, for example) in order to move to a truly sustainable modern society (Robles et al., 2020; Hasan et al., 2021). The ability to recover and valorize nutrient elements from wastewater generates benefits such as complying with effluent nutrient levels required by legislation, reducing eutrophication problems, and providing by-products with economic potential of various kinds, among others (Robles et al., 2020).

At international level, there is no unified environmental legislation to regulate the use of treated wastewater from the animal production industry for irrigation applications. Locally the Chilean legislation NCh 1333regulates the requirements of water quality for several applications, including irrigation; however, it just defines range of pH values (5.5-9.0) for irrigation. For the discharge of industrial liquid residues to the sewer system, the legal provision D.S. 609/1998 of Chile regulates the standards of pH, P, N and biological O demand, amongst others (Table 3). The legal provision D.S. 90/01 of Chile applies for the discharge of liquid residues to superficial water systems and includes the parameters mentioned before (Table 3).

Table 2. Physicochemical processes studied to remove residues and to achieve the reuse of livestock wastewater.

Technology	Advantage	Disadvantage	References
Fenton	Less effluent toxicity, color removal, pollutant mineralization	Toxicity of Fe, no catalyst reuse, low efficiency at high pH for complex wastewater	Domingues et al., 2018; 2021
Photo-Fenton	Improved degradation of organic molecules	UV radiation required, increased costs	Park et al., 2019
Ozonization	Reaction with electron-rich molecules	Incomplete oxidation in complex wastewater, toxic by-products	Gomes et al., 2019; Cheng et al., 2020b; Rekhate and Srivastava, 2020
Photocatalysis	Fast reaction using solar radiation, high mineralization of contaminants	High turbidity of the effluent, effluent filtration with increased costs	Basavarajappa et al., 2020; Cheng et al., 2020b; Kang et al., 2020; Zhao et al., 2020; Domingues et al., 2021
Electrochemical processes	Operation at ambient temperature and pressure, high performance and adaptability to livestock wastewater	High electrode costs, high energy consumption, toxic by-products, organochlorine compound formation from NaCl	Huang et al., 2018; 2019; Garcia-Segura et al., 2019
Electrocoagulation	Simple equipment, operation and automation	Replacement of anodes increases the process costs	Zhang et al., 2018

Table 3. Maximum limit or range of some parameters for the discharge of liquid residues according to Chilean environmental legislation. TP: Total P; TN: total N; BOD: biological oxygen demand.

Parameter	Legal provision D.S. 609/1998	Legal provision D.S. 90/01
pH	5.5-9.0	6.0-8.5
TP, mg L^{-1}	15	10
TN, mg L^{-1}	80	50
BOD, mg L^{-1}	35	35

It is worth mentioning, that the reuse of livestock and poultry wastewater has been explored. There are several technologies assessed in the reuse of livestock wastewater, such as membrane filtration with a high recovery percentage (Table 4) Therefore membrane filtration seems to be the most viable technology for wastewater reuse. In particular, Mansor et al. (2021) developed ultrafiltration membranes able to remove the biological oxygen demand (BOD), chemical oxygen demand (COD), total soluble solids (TSS) and turbidity with an efficiency of 99.8%, 99.7%, 99.8% and 99.6%, respectively. The above compounds are the main source of organic pollutants in the case of dairy industry wastes. Ultrafiltration is a good method for water treatment of economic and ecological importance that should be reused. Table 4 is a compendium of studies that summarizes research efforts pertaining to the reuse of livestock, poultry and dairy wastewater.

Table 4. Reuse of livestock, poultry and dairy industry wastewater and removal efficiency. COD: Chemical oxygen demand; TSS: total soluble solids; BOD: biological oxygen demand; TN: total N; NH_3-N: ammoniacal N.

Type of wastewater	Parameters	Technology	Reuse	Removal efficiency (%)	References
Poultry slurry	COD, TSS, turbidity	Microfiltration	Cleaning, irrigation	100	Goswami and Pugazhenthi, 2020
Cheese whey	BOD, COD, TSS	Ultrafiltration	Cleaning, irrigation	99	Mansor et al., 2021
Pig slurry	P	Sorption with Al	Cleaning, irrigation	94	Banet et al., 2020
Pig slurry	N_2O	Compost	Cleaning, irrigation	87	Matiz-Villamil, et al., 2023
Livestock wastewater	COD, P, N	Microcurrent-assisted multi-soil-layering systems	Cleaning, irrigation	> 80	Liu et al., 2022
Dairy wastewater	BOD, proteins, lipids	Coagulation	Cleaning, irrigation	73	Kurup et al., 2019

Membrane filtration

Actually, a wide spectrum of nutrient removal techniques is employed in wastewater management. Nevertheless, these technologies frequently show inefficiency, allowing nutrients to permeate into aquatic ecosystems. Increased wastewater reuse means the incorporation of tertiary treatments to slurries, such as membrane processes with high nutrient removal efficiency (Table 4) with a concentrate or retentate yield of 20%-40%, a water recovery of 55%-75% for dairy effluents and 50%-90% for swine effluents (Vaishnav et al., 2023). Within this context, their combination with biological treatments emerges as an ecologically conscientious way to succeed secondary treatments by capturing chemical residues from wastewater and converting them into potentially valuable commodities (Vaishnav et al., 2023).

Membrane technologies are a versatile tool used in various sectors from drinking water production to resource recovery. In wastewater treatment, membrane technologies offer a number of advantages over traditional methods, such as less energy consumption, continuous separation, and higher contaminant removal efficiency (Vaishnav et al., 2023). One of the main advantages of membrane technologies is that they can remove contaminants continuously. This is in contrast to traditional methods of wastewater treatment, which are often batch processes that require a down-load time for cleaning and maintenance. Another advantage of membrane technologies is that they can reduce energy consumption, because membranes are able to separate contaminants physically, rather than using chemical or biological processes with higher energy consumption (Quan et al., 2018; Chen et al., 2022). However, membrane technologies also have some disadvantages. One of the main disadvantages is that they can be expensive to install and operate. Another disadvantage is that membranes can become clogged with contaminants, known as fouling, which reduces permeate flux and requires periodic cleaning (Kwon et al., 2021). This occurs when solids and other organic materials are deposited on the surface or within the pores of the membrane. This will reduce permeate flux, requiring more pressure and increasing energy consumption. Membrane fouling is influenced by a number of factors, including membrane properties, roughness and hydrophobicity, flow velocity, transmembrane pressure; temperature, pH, ionic strength and contaminant concentration (Obotey-Ezugbe and Rathilal, 2020; Bera et al., 2022; Vaishnav et al., 2023). However, there is still a gap in knowledge about the use of membranes at low fouling conditions, as well as the search for alternatives to mitigate fouling in order to extend the operational life of these elements.

BIOLOGICAL TREATMENTS

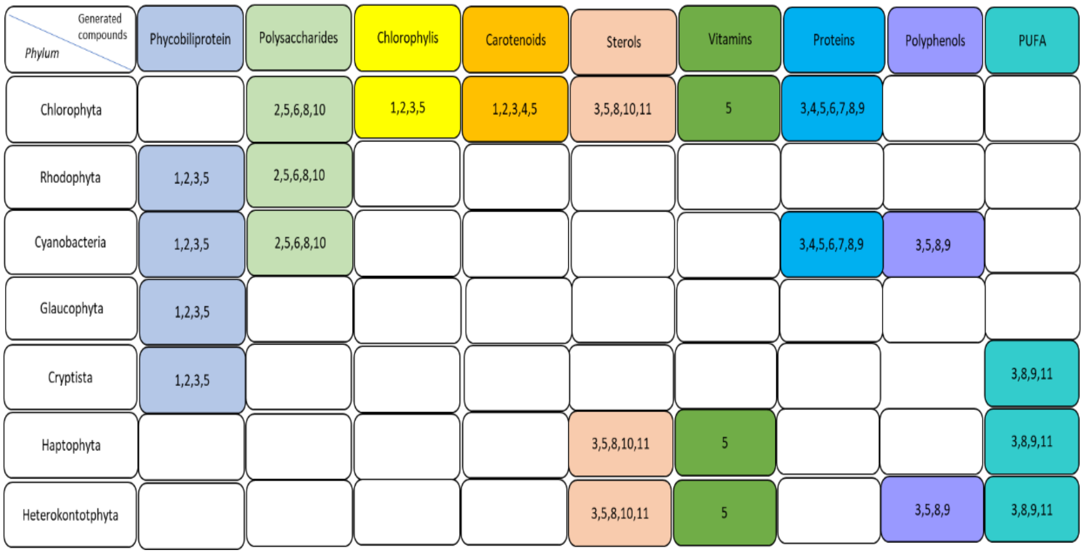
Among the technologies investigated for the recovery and valorization of livestock slurry residues, microalgae and bacteria stand out as the most extensively studied, in particular microalgae-bacteria interactions (López-Sánchez et al., 2022). These biological treatments exhibit a notable edge over chemical procedures or membrane systems due to diminished energy consumption and operational expenses (Crini and Lichtfouse, 2019; Sutherland and Ralph, 2019; Pacheco et al., 2020).

Microalgae

Due to their adaptability to various aquatic environments, microalgae have proven to be an adequate receptor of nutrients from livestock effluents. As previously discussed, these effluents contain macronutrients, such as N and P, along with micronutrients including Ca, Cl, Cr, Co, Cu, Fe, Mg, Mn, K, Si, Na, S, and Zn. This diverse chemical environment promotes the proliferation of microalgae. Employing microalgae-based wastewater treatments effectively assimilates organic matter and nutrients, fulfilling their growth requirements, while concurrently serving as repositories for nutrients and chemical precursors such as proteins, lipids, polysaccharides, vitamins, and beta-carotenes, thus enabling potential product generation like biofuels (Table 5) (Li et al., 2018; 2020). Microalgae-driven biological nutrient removal has undergone extensive scrutiny in the last years (Cheng et al., 2019; Lu et al., 2019; Nagarajan et al., 2020). This process allows the synthesis of valuable commodities at notably cost-effective conditions of approximately US\$0.24 m^{-3} (Figure 1) (Cheng et al., 2020a; Chaudry, 2021).

Table 5. Main species of microalgae and products generated from livestock wastewater and their applications.

Species	Product	Application	References
Botryococcus braunii; *Chlorella zofingiensis*; *Coelastrella striolata*; *Cryptonemia obovata*; *Dunaliella bardawil*; *Dunaliella salina*; *Haematococcus pluvialis*; *Nannochloropsis gaditana*; *Phaeodactylum tricornutum*; *Scenedesmus obliquus*	Carotenoids, pigments	Dyes, food additives, nutritional supplements	Khoo et al., 2019; Koyande et al., 2019; Sathasivam et al., 2019; Zanella and Vianello, 2020
Aulosira fertilissima; *Nostoc muscorum*; *Spirulina platensis*; *Synechocystis salina*	Polysaccharides	Antibacterial, antifungal, antioxidant, anticancer, immunomodulatory, anti-inflammatory, anticoagulant, antitussive, antiglycemic, antilipidemic and antiaging activities, bioplastics	Koutra et al., 2018; Prybylski et al., 2020
Arthrospira platensis; *Chlorella minutissima*; *Chlorella sorokiniana*; *Scenedesmus bijuga* consortia	Proteins	Animal feed, industrial products, personal care products	Moheimani et al., 2018; Fuentes-Tristan et al., 2019; Luo et al., 2019; Orfanoudaki et al., 2019; Amador-Castro et al., 2020
Botryococcus braunii; *Chlorella protothecoides*; *Chlorella sorokiniana*; *Scenedesmus obliquus*	Lipids	Biodiesel, bioethanol, biogas, biohydrogen	Kadir et al., 2018; Khalid et al., 2018; Javed et al., 2019; Maaz et al., 2019
Botryococcus braunii; *Chlorella kessleri*; *Dunaliella tertiolecta*; *Tetraselmis suecica*	Metal nanoparticles	Cosmetic industry, food packaging, textile products	Arévalo-Gallegos et al., 2018; Arya et al., 2018; Pugazhendhi et al., 2018



Generated compounds Phylum	Phycobiliprotein	Polysaccharides	Chlorophylis	Carotenoids	Sterols	Vitamins	Proteins	Polyphenols	PUFA
Chlorophyta		2,5,6,8,10	1,2,3,5	1,2,3,4,5	3,5,8,10,11	5	3,4,5,6,7,8,9		
Rhodophyta	1,2,3,5	2,5,6,8,10							
Cyanobacteria	1,2,3,5	2,5,6,8,10					3,4,5,6,7,8,9	3,5,8,9	
Glaucophyta	1,2,3,5								
Cryptista	1,2,3,5								3,8,9,11
Haptophyta					3,5,8,10,11	5			3,8,9,11
Heterokontotphyta					3,5,8,10,11	5		3,5,8,9	3,8,9,11

Figure 1. Livestock wastewater compounds synthesized by microalgae and their applications[1]. Adapted from López-Sánchez et al., 2022. PUFA: polyunsaturated fatty acids. [1]1: Dyes used in the food, pharmaceutical or cosmetics industries; 2: immunostimulant in the pharmaceutical or cosmetics industry; 3: anti-inflammatory; 4: photo-protection; 5: antioxidant in nutraceuticals; 6: rheological agent in the food industry; 7: collagen stimulant in the cosmetics industry; 8: anti-chronic in the pharmaceutical industry; 9: antimicrobial/antiviral in the pharmaceutical or cosmetics industry; 10: anti-cachectic lipidemic; 11: anti-degenerative in the pharmaceutical industry.

Total carotenoid content for microalgal species ranges between 0.69% and 14.0% of biomass (Koyande et al., 2019). These compounds were applied due to their antioxidant properties as non-allergenic natural colorants, feed supplements, and functional compounds for both human and animal consumption (Khoo et al., 2019; Sathasivam et al., 2019; Zanella and Vianello, 2020). Microalgal protein content spans between 6% and 71% of DM composition (Koyande et al., 2019), being used in the production of personal care products such as UV filters (Fuentes-Tristan et al., 2019; Amador-Castro et al., 2020). Furthermore, microalgae are a prominent third-generation biofuel feedstock due to their high lipid content, with oil production surpassing that of oilseed crops like corn, sunflower, soybean, and palm by 15-300 times (Lee et al., 2020; Poh et al., 2020). Microalgae also yield exopolysaccharides (EPS), compounds of elevated value because of their remarkable attributes, having a recovery percentage in the range of 74%-78% (Cheng et al., 2020a). Beyond their auto-flocculation properties, EPS exhibit antibacterial, antifungal, antioxidant, anticancer, immunomodulatory, anti-inflammatory, anticoagulant, antitussive, antiglycemic, antilipidemic, and antiaging characteristics (Prybylski et al., 2020). Consequently, biological treatments using microalgae offer a viable way for the recovery, transformation and reuse of nutrients from livestock wastewater. Nevertheless, the challenge of scaling up remains, despite successful laboratory-scale trials and high-density cultures, together with the subsequent extraction and purification of generated biomolecules (Li et al., 2020). As microalgae are suspended in the aqueous cultivation medium, biomass and intra/extracellular metabolites require the separation and collection from this medium (Li et al., 2020). Among the foremost technologies for harvesting of microalgal biomass, centrifugation, flocculation, and filtration feature prominently (Singh and Patidar, 2018). Nevertheless, some of these processes have adverse implications at an industrial scale, such as the utilization of environmentally detrimental flocculants, and challenge the subsequent purification of algae and/or their derivatives (Hu et al., 2020).

Microalgae-bacteria consortia

Microalgae-bacteria consortia exhibit a complex interaction of mutualistic and antagonistic relationships (Gradilla-Hernández et al., 2020; Zhang et al., 2021). Within this dynamic, beneficial outcome occurs the synthesis of compounds such as micronutrients and vitamins, along with the enhancement in process efficiency.

In the case of mutualistic bacteria-microalgae interactions, bacteria contribute to the production of compounds favorable for microalgal growth, including micronutrients, vitamins, growth stimulants, and antibiotics that protect microalgae from pathogenic microbes (López-Sánchez et al., 2022). Moreover, the respiratory activity of bacteria releases carbon dioxide — critical for microalgal photosynthesis — increasing dissolved oxygen levels for aerobic bacteria in the environment, thereby mitigating the need for mechanical aeration (Zhang et al., 2021).

Nevertheless, these consortia can also give rise to adverse effects. Nitrifying bacteria can perturb microalgal growth; competition ensues at limited CO_2 concentrations; substances like streptomycin can interfere with photosynthetic mechanisms by impeding electron transport, leading to reduced microalgal growth and biomass accumulation. Table 5 refers to some studies involving microalgae-bacteria consortia in agroindustrial wastewater treatment.

Specific bacteria can take part in a symbiotic alliance with microalgae, exemplified by *Chlorella vulgaris*, where both groups receive mutual benefits. This understanding serves as a pivotal cornerstone for formulating strategies that improve the technical and economic viability of wastewater treatment systems based on bacteria-microalgae consortia. Among the advantages are process simplification, concurrent nitrification and denitrification, increased microalgal survival post-acclimatization due to system robustness, and less sterilization costs associated with livestock wastewater (López-Sánchez et al., 2023). In spite of that, further validation of these systems through ongoing studies is indispensable.

While the unique characteristics of microalgae species make them suitable for particular objectives, most literature predominantly examines monocultures. However, the challenge of maintaining sterile conditions, especially in open-pond systems, prompts exploration into the potential of microalgae consortia with other microorganisms, such as lactic acid bacteria — a promising way that remains relatively unclear.

Future challenges: Lactic acid bacteria as a waste recovery alternative

Lactic acid bacteria (LAB) constitute a diverse group of prokaryotic microorganisms recognized because of their diverse morphology and physiology, chiefly characterized by the fermentation of sugars leading to lactic acid production. Belonging to the order of Lactobacillales, LAB contain six families, 30 genera (primarily *Lactococcus* sp., *Streptococcus* sp., *Leuconostoc* sp. and *Lactobacillus* sp.), and over 300 species (Mora-Villalobos et al., 2020). Thriving in diverse environmental conditions, LAB play many roles, ranging from adapting to ecological niches (e.g., wastewater) to grow at adverse conditions of temperature, pH, and salinity (Vasmara et al., 2021). The LAB produce bacteriocins with antimicrobial attributes that can delay the growth of pathogens (Mora-Villalobos et al., 2020). The biomass is a high-quality feed or probiotic supplement, promoting gut microbiota health, lowering cholesterol, and regulating immune response in consumers. The LAB synthesize lactic and polylactic acids, exhibiting several applications in the food and bioplastic industry (Zou et al., 2024). Moreover, LAB are an auspicious way for functional EPS production, manifesting as high-molecular-weight ionic or non-ionic exocellular polymers (Yildiz and Karatas, 2018; Daba et al., 2021; Korcz and Varga, 2021). Among LAB-derived EPS are dextran, levan, kefiran, and hyaluronic acid. These compounds exert viscosity increasing, emulsifying, texturizing, and stabilizing effects, along with antifungal, antibacterial, antioxidant, and prebiotic attributes (Mantovan et al., 2018; Zhou et al., 2018; Hasheminya et al., 2019; Moradi and Kalanpour, 2019; Martin et al., 2020). Figure 2 summarizes the products obtained after waste recovery using LAB.

There are no studies published about the treatment of livestock wastewater employing LAB. To the best of our knowledge, these microorganisms possess the metabolic pathways for bioproduct formation and recovery from these effluents. However, according to the nutritional requirements LAB need co-fermentations that involves the combination of two types of wastewater or wastes to establish the optimal conditions for microbial proliferation (Vasmara et al., 2021; Zhao et al., 2022). The incorporation of strains with probiotic attributes in waste and/or effluent treatment not only promotes the production of bioproducts like organic acids and exopolysaccharides but also yields probiotic biomass, valuable as animal feed or used in agricultural applications (Zhong et al., 2021; Pekkoh et al., 2022; Sadeghi et al., 2022). These unique attributes of LAB make their exploration for livestock wastewater treatment and waste recovery a promising challenge.

Finally, Figure 3 offers a conceptual representation of an integrated wastewater treatment system, combining prevalent filtration technologies and biological systems. Wastewater could undergo a tertiary treatment by ultrafiltration membranes, enabling water reuse within the facility and/or agricultural irrigation. Simultaneously, the retentate fraction from the ultrafiltration stage could undergo a biological transformation process involving microalgae, for example of the *Chlorella* genus, facilitating the recovery of nutrients viable in pharmaceutical, food, agricultural, or livestock applications, reintegrating them into productive cycle. Furthermore, this process may generate biofuels such as biogas for energy supply within the same tertiary treatment phase.

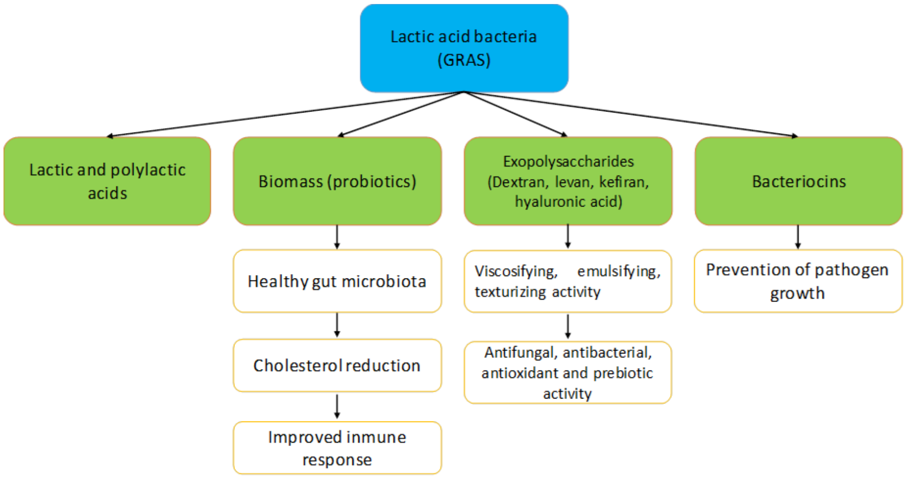


Figure 2. Products obtained from livestock and poultry effluents by using lactic acid bacteria. GRAS: Generally recognized as safe.

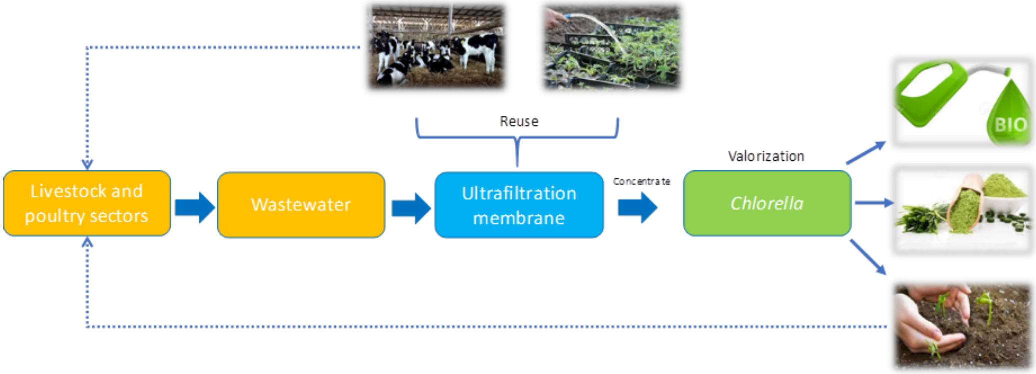


Figure 3. Diagram of the proposed integrated treatment system for the reuse and recovery of livestock and poultry wastewater.

CONCLUSIONS

An integrated system for livestock and poultry wastewater combining membrane filtration with bacteria and microalgae offers an ecological sound, sustainable bioprocess technology for water reuse and waste valorization. Ultrafiltration membrane technology is important in wastewater reuse due to their remarkable capacity achieving nutrient removal rates of up to 100%. This technology enables the reuse of water within the same production process or its use as irrigation water in agriculture. Furthermore, the integration of this separation process with biological systems enables the creation of valuable biotechnological compounds from wastewater nutrients. Microalgae and bacteria act as precursors, generating by-products of substantial value via their metabolic pathways and compounds like food supplements and health promoting agents. In particular, lactic acid bacteria offer promising ways by co- fermentation strategies for livestock wastewater utilization and nutrient consumption. In the future, the combination of membrane filtration with biological systems — specifically the interplay between ultrafiltration and microalgae — will play a central role in novel wastewater reuse and nutrient recovery for the livestock and poultry sector. This holistic approach agrees perfectly with the principles of circular economy, ensuring an efficient and effective management of wastewater treatment facilities. However, the realization of these benefits at an industrial scale requires more studies to facilitate the implementation of these cutting-edge technologies.

Author contribution

Investigation: O.H. Writing-original draft: O.H. Writing-review & editing: O.H., J.B. Visualization: O.H. Supervision: J.B. All authors reviewed the final version and approved the manuscript before submission.

Acknowledgements

We would like to thank the Postgraduate School of the Universidad de Concepción and the National Agency for Investigation and Development (ANID) for granting a scholarship (2020-21200950) to the first author to carry out her Ph.D. study.

References

Åkerman, M., Humalisto, N., Pitzen, S. 2020. Material politics in the circular economy: The complicated journey from manure surplus to resource. Geoforum 116:73-80. doi:10.1016/j.geoforum.2020.07.013.

Amador-Castro, F., Rodriguez-Martinez, V., Carrillo-Nieves, D. 2020. Robust natural ultraviolet filters from marine ecosystems for the formulation of environmental friendlier bio-sunscreens. Science of the Total Environment 749:141576. doi:10.1016/j.scitotenv.2020.141576.

Arévalo-Gallegos, A., Garcia-Perez, J.S., Carrillo-Nieves, D., Ramirez-Mendoza, R.A., Iqbal, H.M.N., Parra-Saldívar, R. 2018. *Botryococcus braunii* as a bioreactor for the production of nanoparticles with antimicrobial potentialities. International Journal of Nanomedicine 13:5591-5604. doi:10.2147/IJN.S174205.

Artukmetov, Z., Nasirov, B., Aliev, J., Kamolova, N. 2021. Composition of waste water from poultry factories and their suitability for irrigation of agricultural crops (as an example of Tashkent province, Uzbekistan). E3S Web of Conferences 244:01018. doi:10.1051/e3sconf/202124401018.

Arya, A., Gupta, K., Chundawat, T.S., Vaya, D. 2018. Biogenic synthesis of copper and silver nanoparticles using green alga *Botryococcus braunii* and its antimicrobial activity. Bioinorganic Chemistry and Applications 2018:7879403. doi:10.1155/2018/7879403.

Banet, T., Massey, M.S., Zohar, I., Litaor, M.I., Ippolito, J.A. 2020. Phosphorus removal from swine wastewater using aluminium-based water treatment residuals. Resources, Conservation & Recycling: X 6:100039. doi:10.1016/j.rcrx.2020.100039.

Basavarajappa, P., Patil, S., Ganganagappa, N., Raghava, K., Raghu, A., Venkata, C. 2020. Recent progress in metal-doped TiO_2, non-metal doped/codoped TiO_2 and TiO_2 nanostructured hybrids for enhanced photocatalysis. International Journal of Hydrogen Energy 45:7764-7778. doi:10.1016/j.ijhydene.2019.07.241.

Bera, S.P., Godhaniya, M., Kothari, C. 2022. Emerging and advanced membrane technology for wastewater treatment: A review. Journal of Basic Microbiology 62:245-259. doi:10.1002/jobm.202100259.

Chaudry, S. 2021. Integrating microalgae cultivation with wastewater treatment: A peek into economics. Applied Biochemistry and Biotechnology 193:3395-3406. doi:10.1007/s12010-021-03612-x.

Chen, F., Ma, J., Zhu, Y., Li, X., Yu, H., Sun, Y. 2022. Biodegradation performance and anti-fouling mechanism of an ICME/electro-biocarriers-MBR system in livestock wastewater (antibiotic-containing) treatment. Journal of Hazardous Materials 426:128064. doi:10.1016/j.jhazmat.2021.128064.

Chen, W., Oldfield, T.L., Patsios, S.I., Holden, N.M. 2020. Hybrid life cycle assessment of agro-industrial wastewater valorisation. Water Research 170:115275. doi:10.1016/j.watres.2019.115275.

Cheng, H.H., Narindri, B., Chu, H., Whang, L.M. 2020a. Recent advancement on biological technologies and strategies for resource recovery from swine wastewater. Bioresource Technology 303:122861. doi:10.1016/j.biortech.2020.122861.

Cheng, D., Ngo, H.H., Guo, W., Chang, S.W., Nguyen, D.D., Liu, Y., et al. 2020b. A critical review on antibiotics and hormones in swine wastewater: Water pollution problems and control approaches. Journal of Hazardous Materials 387:121682. doi:10.1016/j.jhazmat.2019.121682.

Cheng, P., Osei-Wusu, D., Zhou, C., Wang, Y., Xu, Z., Chang, T., et al. 2019. The effects of refractory pollutants in swine wastewater on the growth of *Scenedesmus* sp. with biofilm attached culture. International Journal of Phytoremediation 22:241-250. doi:10.1080/15226514.2019.1658706.

Crini, G., Lichtfouse, E. 2019. Advantages and disadvantages of techniques used for wastewater treatment. Environmental Chemistry Letters 17:145-155. doi:10.1007/s10311-018-0785-9.

Daba, G.M., Elnahas, M.O., Elkhateeb, W.A. 2021. Contributions of exopolysaccharides from lactic acid bacteria as biotechnological tools in food, pharmaceutical, and medical applications. International Journal of Biological Macromolecules 173:79-89. doi:10.1016/j.ijbiomac.2021.01.110.

Daneshvar, E., Zarrinmehr, M.J., Koutra, E., Kornaros, M., Farhadian, O., Bhatnagar, A. 2019. Sequential cultivation of microalgae in raw and recycled dairy wastewater: Microalgal growth, wastewater treatment and biochemical composition. Bioresource Technology 273:556-564. doi:10.1016/j.biortech.2018.11.059.

de Matos Nascimento, A., de Paula, V.R., Oliveira-Dias, E.H., da Costa-Carneiro, J., Otenio, M.H. 2020. Quantitative microbial risk assessment of occupational and public risks associated with bioaerosols generated during the application of dairy cattle wastewater as biofertilizer. Science of the Total Environment 745:140711. doi:10.1016/j.scitotenv.2020.140711.

de Mendonça, H.V., Ometto, J.P.H.B., Otenio, M.H., Marques, I.P.R., dos Reis, A.J.D. 2018. Microalgae-mediated bioremediation and valorization of cattle wastewater previously digested in a hybrid anaerobic reactor using a photobioreactor: Comparison between batch and continuous operation. Science of the Total Environment 633:1-11. doi:10.1016/j.scitotenv.2018.03.157.

Domingues, E., Fernandes, E., Gomes, J., Martins, R.C. 2021. Advanced oxidation processes perspective regarding swine wastewater treatment. Science of the Total Environment 776:145958. doi:10.1016/j.scitotenv.2021.145958.

Domingues, E., Gomes, J., Quina, M., Quinta-Ferreira, R., Martins, R. 2018. Detoxification of olive mill wastewaters by Fenton's process. Catalysts 8:662. doi:10.3390/catal8120662.

FAO. 2021. Dairy market review: Overview of global dairy market developments in 2020. April 2021. FAO, Rome, Italy.

Ferreira, A., Marques, P., Ribeiro, B., Assemany, P., de Mendonça, H.V., Barata, A., et al. 2018. Combining biotechnology with circular bioeconomy: From poultry, swine, cattle, brewery, dairy and urban wastewaters to biohydrogen. Environmental Research 164:32-38. doi:10.1016/j.envres.2018.02.007.

Fuentes-Tristan, S., Parra-Saldivar, R., Iqbal, H.M.N., Carrillo-Nieves, D. 2019. Bioinspired biomolecules: Mycosporine-like amino acids and scytonemin from *Lyngbya* sp. with UV-protection potentialities. Journal of Photochemistry and Photobiology B: Biology 201:111684. doi:10.1016/j.jphotobiol.2019.111684.

Garcia-Segura, S., Mostafa, E., Baltruschat, H. 2019. Electrogeneration of inorganic chloramines on boron-doped diamond anodes during electrochemical oxidation of ammonium chloride, urea and synthetic urine matrix. Water Research 160:107-117. doi:10.1016/j.watres.2019.05.046.

Gomes, J., Frasson, D., Pereira, J., Gonçalves, F., Castro, L., Quinta-Ferreira, R., et al. 2019. Ecotoxicity variation through parabens degradation by single and catalytic ozonation using volcanic rock. Chemical Engineering Journal 360:30-37. doi:10.1016/j.cej.2018.11.194.

Goswami, K., Pugazhenthi, G. 2020. Treatment of poultry slaughterhouse wastewater using tubular microfiltration membrane with fly ash as key precursor. Journal of Water Process Engineering 37:101361. doi:10.1016/j.jwpe.2020.101361.

Gradilla-Hernández, M.S., García-González, A., Gschaedler, A., Herrera-López, E.J., González-Avila, M., García-Gamboa, R., et al. 2020. Applying differential neural networks to characterize microbial interactions in an ex vivo gastrointestinal gut simulator. Processes 8:593. doi:10.3390/pr8050593.

Hasan, M.N., Altaf, M.M., Khan, N.A., Kahn, A.H., Kahn, A.A., Ahmed, S., et al. 2021. Recent technologies for nutrient removal and recovery from wastewaters: A review. Chemosphere 277:130328. doi:10.1016/j.chemosphere.2021.130328.

Hasheminya, S.M., Mokarram, R.R., Ghanbarzadeh, B., Hamishekar, H., Kafil, H.S., Dehghannya, J. 2019. Development and characterization of biocomposite films made from kefiran, carboxymethyl cellulose and *Satureja Khuzestanica* essential oil. Food Chemistry 289:443-452. doi:10.1016/j.foodchem.2019.03.076.

Hu, H., Li, X., Wu, S., Yang, C. 2020. Sustainable livestock wastewater treatment via phytoremediation: Current status and future perspectives. Bioresource Technology 315:123809. doi:10.1016/j.biortech.2020.123809.

Huang, K.L., Liu, C.C., Ma, C.Y., Chen, T.T. 2019. Effects of operating parameters on electrochemical treatment of swine wastewater. International Journal of Electrochemical Science 14:11325-11339. doi:10.20964/2019.12.43.

Huang, K.L., Wei, K.C., Chen, M.H., Ma, C.Y. 2018. Removal of organic and ammonium nitrogen pollutants in swine wastewater using electrochemical advanced oxidation. International Journal of Electrochemical Science 13:11418-11431. doi:10.20964/2018.12.32.

Hülsen, T., Hsieh, K., Tait, S., Barry, E.M., Puyol, D., Batstone, D.J. 2018. White and infrared light continuous photobioreactors for resource recovery from poultry processing wastewater – A comparison. Water Research 144:665-676. doi:10.1016/j.watres.2018.07.040.

Javed, F., Aslam, M., Rashid, N., Shamair, Z., Khan, A.L., Yasin, M., et al. 2019. Microalgae-based biofuels, resource recovery and wastewater treatment: A pathway towards sustainable biorefinery. Fuel 255:115826. doi:10.1016/j.fuel.2019.115826.

Kadir, W., Lam, M., Uemura, Y., Lim, J.W., Lee, K. 2018. Harvesting and pre-treatment of microalgae cultivated in wastewater for biodiesel production: A review. Energy Conversion and Management 171:1416-1429. doi:10.1016/j.enconman.2018.06.074.

Kang, J., Zhou, L., Duan, X., Sun, H., Wang, S. 2020. Catalytic degradation of antibiotics by metal-free catalysis over nitrogen-doped graphene. Catalysis Today 357:341-349. doi:10.1016/j.cattod.2018.12.002.

Khalid, A.A.H., Yaakob, Z., Abdullah, S.R.S., Takriff, M.S. 2018. Growth improvement and metabolic profiling of native and commercial *Chlorella sorokiniana* strains acclimatized in recycled agricultural wastewater. Bioresource Technology 247:930-939. doi:10.1016/j.biortech.2017.09.195.

Khanal, G., Maraseni, T., Thapa, A., Devkota, N., Paudel, U.R., Khanal, C.K. 2023. Managing water scarcity via rainwater harvesting system in Kathmandu Valley, Nepal: People's awareness, implementation challenges and way forward. Environmental Development 46:100850. doi:10.1016/j.envdev.2023.100850.

Khoo, K.S., Lee, S.Y., Ooi, C.W., Fu, X., Miao, X., Ling, T.C., et al. 2019. Recent advances in biorefinery of astaxanthin from *Haematococcus pluvialis*. Bioresource Technology 288:121606. doi:10.1016/j.biortech.2019.121606.

Korcz, V., Varga, L. 2021. Exopolysaccharides from lactic acid bacteria: Techno-functional application in the food industry. Trends in Food Science & Technology 110:375-384. doi:10.1016/j.tifs.2021.02.014.

Koutra, E., Economou, C.N., Tsafrakidou, P., Kornaros, M. 2018. Bio-based products from microalgae cultivated in digestates. Trends in Biotechnology 36:819-833. doi:10.1016/j.tibtech.2018.02.015.

Koyande, A.K., Chew, K.W., Rambabu, K., Tao, Y., Chu, D.T., Show, P.L. 2019. Microalgae: A potential alternative to health supplementation for humans. Food Science and Human Wellness 8:16-24. doi:10.1016/j.fshw.2019.03.001.

Kurup, G.G., Adhikari, B., Zisu, B. 2019. Recovery of proteins and lipids from dairy wastewater using food grade sodium lignosulphonate. Water Resources and Industry 22:100114. doi:10.1016/j.wri.2019.100114.

Kwon, D., Bae, W., Kim, J. 2021. Hybrid forward osmosis/membrane distillation integrated with anaerobic fluidized bed bioreactor for advanced wastewater treatment. Journal of Hazardous Materials 404:124160. doi:10.1016/j.jhazmat.2020.124160.

Lee, H., Jeong, D., Im, S.J., Jang, A. 2020. Optimization of alginate bead size immobilized with *Chlorella vulgaris* and *Chlamydomonas reinhardtii* for nutrient removal. Bioresource Technology 302:122891. doi:10.1016/j.biortech.2020.122891.

Lee, K., Jepson, W. 2020. Drivers and barriers to urban water reuse: A systematic review. Water Security 11:100073. doi:10.1016/j.wasec.2020.100073.

Li, W., Ren, M., Duo, L., Li, J., Wang, S., Sun, Y., et al. 2020. Fermentation characteristics of *Lactococcus lactis* subsp. *lactis* isolated from naturally fermented dairy products and screening of potential starter isolates. Frontiers in Microbiology 11:1794. doi:10.3389/fmicb.2020.01794.

Li, X., Yang, W.L., He, H., Wu, S., Zhou, Q., Yang, C., et al. 2018. Responses of microalgae *Coelastrella* sp. to stress of cupric ions in treatment of anaerobically digested swine wastewater. Bioresource Technology 251:274-279. doi:10.1016/j.biortech.2017.12.058.

Liu, S., Qiu, D., Lu, F., Wang, Y., Wang, Z., Feng, X., et al. 2022. *Acorus calamus* L. constructed wetland-microbial fuel cell for Cr(VI)-containing wastewater treatment and bioelectricity production. Journal of Environmental Chemical Engineering 10:107801. doi:10.1016/j.jece.2022.107801.

López-Pacheco, I.Y., Carrillo-Nieves, D., Salinas-Salazar, C., Silva-Núñez, A., Arévalo-Gallegos, A., Barceló, D., et al. 2019. Combination of nejayote and swine wastewater as a medium for *Arthrospira maxima* and *Chlorella vulgaris* production and wastewater treatment. Science of the Total Environment 676:356-367. doi:10.1016/j.scitotenv.2019.04.278.

López-Sánchez, A., Silva-Gálvez, A.L., González-López, M.E., Díaz-Vázquez, D., Orozco-Nunnelly, D.A., Novoa-Leiva, I., et al. 2023. Valorization of livestock waste through combined anaerobic digestion and microalgae-based treatment in México: A techno-economic analysis for distributed biogas generation, animal feed production, and carbon credits trading. Environmental Technology & Innovation 32:103321. doi:10.1016/j.eti.2023.103321.

López-Sánchez, A., Silva-Gálvez, A.L., Zárate-Aranda, J.E., Yebra-Montes, C., Orozco-Nunnelly, D.A., Carrillo-Nieves, D., et al. 2022. Microalgae-mediated bioremediation of cattle, swine and poultry digestates using mono- and mixed-cultures coupled with an optimal mixture design. Algal Research 64:102717. doi:10.1016/j.algal.2022.102717.

Lu, W., Asraful Alam, M., Liu, S., Xu, J., Parra Saldivar, R. 2019. Critical processes and variables in microalgae biomass production coupled with bioremediation of nutrients and CO_2 from livestock farms: A review. Science of the Total Environment 716:135247. doi:10.1016/j.scitotenv.2019.135247.

Luo, L., Ren, H., Pei, X., Xi, G., Xing, D., Dai, Y., et al. 2019. Simultaneous nutrition removal and high-efficiency biomass and lipid accumulation by microalgae using anaerobic digested effluent from cattle manure combined with municipal wastewater. Biotechnology for Biofuels 12:218. doi:10.1186/s13068-019-1553-1.

Lv, J., Liu, Y., Feng, J., Liu, Q., Nan, F., Xie, S. 2018. Nutrients removal from undiluted cattle farm wastewater by the two-stage process of microalgae-based wastewater treatment. Bioresource Technology 264:311-318. doi:10.1016/j.biortech.2018.05.085.

Maaz, M., Yasin, M., Aslam, M., Kumar, G., Atabani, A.E., Idrees, M., et al. 2019. Anaerobic membrane bioreactors for wastewater treatment: Novel configurations, fouling control and energy considerations. Bioresource Technology 283:358-372. doi:10.1016/j.biortech.2019.03.061.

Manasfi, R., Brienza, M., Ait-Mouheb, N., Montemurro, N., Perez, S., Chiron, S. 2021. Impact of long-term irrigation with municipal reclaimed wastewater on the uptake and degradation of organic contaminants in lettuce and leek. Science of the Total Environment 765:142742. doi:10.1016/j.scitotenv.2020.142742.

Mansor, E.S., Ali, E.A., Shaban, A.M. 2021. Tight ultrafiltration polyethersulfone membrane for cheese whey wastewater treatment. Chemical Engineering Journal 407:127175. doi:10.1016/j.cej.2020.127175.

Mantovan, J., Bersaneti, G.T., Faria-Tischer, P.C.S., Celligoi, M.A.P.C., Mali, S. 2018. Use of microbial levan in edible films based on cassava starch. Food Packaging and Shelf Life 18:31-36. doi:10.1016/j.fpsl.2018.08.003.

Martin, A.A., Sassaki, G.L., Sierakowski, M.R. 2020. Effect of adding galactomannans on some physical and chemical properties of hyaluronic acid. International Journal of Biological Macromolecules 144:527-535. doi:10.1016/j.ijbiomac.2019.12.114.

Matiz-Villamil, A., Méndez-Carranza, K.J., Pascagaza-Pulido, A.F., Rendón-Rendón, T., Noriega-Noriega, J., Pulido-Villamarín, A. 2023. Trends in the management of organic swine farm waste by composting: A systematic review. Heliyon 9:e18208. doi:10.1016/j.heliyon.2023.e18208.

Moheimani, N.R., Vadiveloo, A., Ayre, J.M., Pluske, J.R. 2018. Nutritional profile and in vitro digestibility of microalgae grown in anaerobically digested piggery effluent. Algal Research 35:362-369. doi:10.1016/j.algal.2018.09.007.

Moradi, Z., Kalanpour, N. 2019. Kefiran, a branched polysaccharide: Preparation, properties and applications: a review. Carbohydrate Polymers 223:115100. doi:10.1016/j.carbpol.2019.115100.

Mora-Villalobos, J.A., Montero-Zamora, J., Barboza, N., Rojas-Garbanzo, C., Usaga, J., Redondo-Solano, M. et al. 2020. Multi-product lactic acid bacteria fermentations: A review. Fermentation 6:23. doi:10.3390/fermentation6010023.

Nagarajan, D., Lee, D.J., Chen, C.Y., Chang, J.S. 2020. Resource recovery from wastewaters using microalgae-based approaches: A circular bioeconomy perspective. Bioresource Technology 302:122817. doi:10.1016/j.biortech.2020.122817.

Niquice-Janeiro, C., Marques-Arsenio, A., Brito, R.M.C.L., van Lier, J.B. 2020. Use of (partially) treated municipal wastewater in irrigated agriculture; potentials and constraints for sub-Saharan Africa. Physics and Chemistry of the Earth 118-119:102906. doi:10.1016/j.pce.2020.102906.

Obotey-Ezugbe, E., Rathilal, S. 2020. Membrane technologies in wastewater treatment: A review. Membranes 10:89. doi:10.3390/membranes10050089.

Oliveira, J.F., Fia, R., Fia, F.R.L., Rodrigues, F.N., Matos, M.P., Siniscalchi, L.A.B. 2020. Principal component analysis as a criterion for monitoring variable organic load of swine wastewater in integrated biological reactors UASB, SABF and HSSF-CW. Journal of Environmental Management 262:110386. doi:10.1016/j.jenvman.2020.110386.

Orfanoudaki, M., Hartmann, A., Karsten, U., Ganzera, M. 2019. Chemical profiling of mycosporine-like amino acids in twenty-three red algal species. Journal of Phycology 55:393-403. doi:10.1111/jpy.12827.

Oueslati, A., Montevecchi, G., Antonelli, A., Mansour, H.B. 2021. Short-time irrigation on young olive tree (*Olea europaea* L. cv. *Chemlali*) with untreated industrial poultry wastewater: investigation of growth parameters and leaves chemical composition. Environmental Science and Pollution Research International 28:50420-50429. doi:10.1007/s11356-021-14261-2.

Pacheco, D., Rocha, A.C., Pereira, L., Verdelhos, T. 2020. Microalgae water bioremediation: Trends and hot topics. Applied Sciences 10:1886. doi:10.3390/app10051886.

Park, J., Shin, D., Lee, J. 2019. Treatment of high-strength animal industrial wastewater using photo-assisted Fenton oxidation coupled to photocatalytic technology. Water 11:1553. doi:10.3390/w11081553.

Patwa, N., Sivarajah, U., Seetharaman, A., Sarkar, S., Maiti, K., Hingorani, K. 2021. Towards a circular economy: An emerging economies context. Journal of Business Research 122:725-735. doi:10.1016/j.jbusres.2020.05.015.

Pekkoh, J., Chaichana, C., Thurakit, T., Phinyo, K., Lomakool, S., Ruangrit, K., et al. 2022. Dual-bioaugmentation strategy to enhance the formation of algal-bacteria symbiosis biofloc in aquaculture wastewater supplemented with agricultural wastes as an alternative nutrient sources and biomass support materials. Bioresource Technology 359:127469. doi:10.1016/j.biortech.2022.127469.

Poh, Z.L., Kadir, W.N.A., Lam, M.K., Uemura, Y., Suparmaniam, U., Lim, J.W., et al. 2020. The effect of stress environment towards lipid accumulation in microalgae after harvesting. Renewable Energy 154:1083-1091. doi:10.1016/j.renene.2020.03.081.

Prybylski, N., Toucheteau, C., El Alaoui, H., Bridiau, N., Maugard, T., Abdelkafi, S., et al. 2020. Bioactive polysaccharides from microalgae. p. 533-571. In Jacob-Lopes, E., Manzoni-Maroneze, M., Queiroz, M.I., Queiroz-Zepka, L. (eds.) Handbook of microalgae-based processes and products. Academic Press, Cambridge, Massachusetts, USA. doi:10.1016/b978-0-12-818536-0.00020-8.

Pugazhendhi, A., Prabakar, D., Jacob, J.M., Karuppusamy, I., Saratale, R.G. 2018. Synthesis and characterization of silver nanoparticles using *Gelidium amansii* and its antimicrobial property against various pathogenic bacteria. Microbial Pathogenesis 114:41-45. doi:10.1016/j.micpath.2017.11.013.

Quan, X., Huang, K., Li, M., Lan, M., Li, B. 2018. Nitrogen removal performance of municipal reverse osmosis concentrate with low C/N ratio by membrane-aerated biofilm reactor. Frontiers of Environmental Science & Engineering 12:5. doi:10.1007/s11783-018-1047-6.

Rekhate, C., Srivastava, J.K. 2020. Recent advances in ozone-based advanced oxidation processes for treatment of wastewater- A review. Chemical Engineering Journal Advances 3:100031. doi:10.1016/j.ceja.2020.100031.

Robles, A., Aguado, D., Barat, R., Borrás, L., Bouzas, A., Gimenez, J.B., et al. 2020. New frontiers from removal to recycling of nitrogen and phosphorus from wastewater in the circular economy. Bioresource Technology 300:122673. doi:10.1016/j.biortech.2019.122673.

Sadeghi, A., Ebrahimi, M., Shahryari, S., Kharazmi, M.S., Jafari, S.M. 2022. Food applications of probiotic yeasts; focusing on their techno-functional, postbiotic and protective capabilities. Trends in Food Science & Technology 128:278-295. doi:10.1016/j.tifs.2022.08.018.

Sarawaneeyaruk, S., Lorliam, W., Krajangsang, S., Pringsulaka, O. 2019. Enhancing plant growth under municipal wastewater irrigation by plant growth promoting rhizospheric *Bacillu*s spp. Journal of King Saud University - Science 31:384-389. doi:10.1016/j.jksus.2018.04.027.

Sathasivam, R., Radhakrishnan, R., Hashem, A., Abd Allah, E.F. 2019. Microalgae metabolites: A rich source for food and medicine. Saudi Journal of Biological Sciences 26:709-722. doi:10.1016/j.sjbs.2017.11.003.

Shen, J., Wang, C., Liu, Y., Hu, C., Xin, Y., Ding, N., et al. 2018. Effect of ultrasonic pretreatment of the dairy manure on the electricity generation of microbial fuel cell. Biochemical Engineering Journal 129:44-49. doi:10.1016/j.bej.2017.10.013.

Singh, G., Patidar, S.K. 2018. Microalgae harvesting techniques: A review. Journal of Environmental Management 217:499-508. doi:10.1016/j.jenvman.2018.04.010.

Sutherland, D.L., Ralph, P.J. 2019. Microalgal bioremediation of emerging contaminants - opportunities and challenges. Water Research 164:114921. doi:10.1016/j.watres.2019.114921.

Thapa, A., Khanal, G., Mahapatra, S.K., Devkota, N., Mahato, S., Paudel, U.R. 2022. Identifying determinants of sustainable water management at the household level through rainwater harvesting systems in Nepal. Water Policy 24:1676-1691. doi:10.2166/wp.2022.113.

Tsai, W.T. 2018. Regulatory promotion and benefit analysis of biogas-power and biogas-digestate from anaerobic digestion in Taiwan’s livestock industry. Fermentation 4:57 doi:10.3390/fermentation4030057.

Unfried, K., Kis-Katos, K., Poser, T. 2022. Water scarcity and social conflict. Journal of Environmental Economics and Management 113:102633. doi:10.1016/j.jeem.2022.102633.

Vaishnav, S., Saini, T., Chauhan, A., Gaur, G.K., Tiwari, R., Dutt, T., et al. 2023. Livestock and poultry farm wastewater treatment and its valorization for generating value-added products: Recent updates and way forward. Bioresource Technology 382:129170. doi:10.1016/j.biortech.2023.129170.

Vasmara, C., Marchetti, R., Carminati, D. 2021. Wastewater from the production of lactic acid bacteria as feedstock in anaerobic digestion. Energy 229:120740. doi:10.1016/j.energy.2021.120740.

Xie, W., Chen, Q.F., Wu, L., Yang, H., Xu, J., Zhang, Y. 2020. Coastal saline soil aggregate formation and salt distribution are affected by straw and nitrogen application: A 4-year field study. Soil and Tillage Research 198:104535. doi:10.1016/j.still.2019.104535.

Yaashikaa, P.R., Kumar, P.S., Varjani, S. 2022. Valorization of agro-industrial wastes for biorefinery process and circular bioeconomy: A critical review. Bioresource Technology 343:126126. doi:10.1016/j.biortech.2021.126126.

Yildiz, H., Karatas, N. 2018. Microbial exopolysaccharides: Resources and bioactive properties. Process Biochemistry 72:41-46. doi:10.1016/j.procbio.2018.06.009.

Zanella, L., Vianello, F. 2020. Microalgae of the genus *Nannochloropsis*: Chemical composition and functional implications for human nutrition. Journal of Functional Foods 68:103919. doi:10.1016/j.jff.2020.103919.

Zhang, C., Li, S., Ho, S.H. 2021. Converting nitrogen and phosphorus wastewater into bioenergy using microalgae-bacteria consortia: A critical review. Bioresource Technology 342:126056. doi:10.1016/j.biortech.2021.126056.

Zhang, X., Lin, H., Hu, B. 2018. The effects of electrocoagulation on phosphorus removal and particle settling capability in swine manure. Separation and Purification Technology 200:112-119. doi:10.1016/j.seppur.2018.02.025.

Zhao, T., Tashiro, Y., Sonomoto, K. 2022. Construction and metabolic analysis of acetone-butanol-ethanol fermentation using mixed acetic acid and lactic acid in wastewater. Industrial Crops and Products 187:115503. doi:10.1016/j.indcrop.2022.115503.

Zhao, H., Tian, C., Mei, J., Wong, P.K. 2020. Synergistic effect and mechanism of catalytic degradation toward antibiotic contaminants by amorphous goethite nanoparticles decorated graphitic carbon nitride. Chemical Engineering Journal 390:124551. doi:10.1016/j.cej.2020.124551.

Zheng, T., Li, P., Ma, X., Sun, X., Wu, C., Wang, Q., et al. 2019. Pilot-scale experiments on multilevel contact oxidation treatment of poultry farm wastewater using saran lock carriers under different operation model. Journal of Environmental Sciences (China) 77:336-345. doi:10.1016/j.jes.2018.09.005.

Zhong, Y., Liu, H., Li, H., Lu, Q., Sun, Y. 2021. Does exogenous carbon source always promote algal biomass and nutrients removal in algal-bacterial wastewater remediation? Journal of Cleaner Production 281:125371. doi:10.1016/j.jclepro.2020.125371.

Zhou, Q., Feng, F., Yang, Y., Zhao, F., Du, R., Zhou, Z., et al. 2018. Characterization of a dextran produced by *Leuconostoc pseudomesenteroides* XG5 from homemade wine. International Journal of Biological Macromolecules 107:2234-2241. doi:10.1016/j.ijbiomac.2017.10.098.

Zhou, Q., Lin, Y., Yang, C., Tang, W., Wu, S., Li, D., et al. 2019. Effects of copper ions on removal of nutrients from swine wastewater and on release of dissolved organic matter in duckweed systems. Water Research 158:171-181. doi:10.1016/j.watres.2019.04.036.

Zou, F., Huo, Y., Gao, W., Dai, M., Zhao, G., Zhang, S. 2024. Physical, microbiological and sensory characterization of yogurt fermented by *Weissella confusa* SW1 and traditional starters. LWT – Food Science and Technology 201:116229. doi:10.1016/j.lwt.2024.116229.