Comparative Analysis for Quantification and Identification of Beverages Industries Effluent of Pakistan Using Advance Multivariate Clustering

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Abstract

The water quality is perpetually deteriorating at an alarming rate due to industrial effluent. The treatment and disposal of wastewater, and its reutilization, remain critical concerns for the sustainable consumption of water in the food and beverage sector. In this paper, a comparative analysis of effluents from two beverage industries has been conducted using wastewater chemistry. Both industries are spatially located along the water channel (Nullah) in the industrial estate areas of two major cities (Rawalpindi and Peshawar) in Pakistan. Initial wastewater characterization was conducted through composite sampling techniques to assess compliance with National Environmental Quality Standards for industrial effluent. Descriptive statistical analysis, correlation matrix, and Multiple Linear Regression analysis were performed to identify and quantify the effluent constituents. The effluent from beverage industries exhibited high concentrations of Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD), which degrade the quality of water bodies. Treatment of wastewater in the food and beverage sector is important for water recycling, resource recovery, and environmental protection. In novel approaches to circular economy principles, the consumption and management of water can facilitate resource recovery, leading to higher sustainability and productivity in food production. In water-stressed countries like Pakistan, recycled wastewater can mitigate the adverse environmental and socio-economic impacts. The utilization of wastewater treatment plants, employing chemical, physical, and biological treatment methods to remove sugar, flavors, and color additives, can reduce BOD and COD levels. Considering the large volume of wastewater, it is highly recommended to reuse and recycle the effluent after initial treatment through efficient technologies to minimize organic pollutant loads.

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Introduction

Pakistan is facing shortage of freshwater resources, and it is expected to suffer 31 million acre-feet (MAF) by 2025 (Natasha et al., 2020). Given its agrarian economy, where agriculture contributes to 26 % of its gross domestic product (GDP) and about 70 % of the population is connected with agriculture (Mahmood & Munir, 2018). Although freshwater sources are renewable in the long term, they have finite withdrawal limits. In countries with dense population like Pakistan, the withdrawal surpassed, resulting in the depletion of groundwater and surface water sources. Freshwater resources are rapidly diminishing due to uncontrolled population growth, urbanization and industrialization, pushing Pakistan in the list of water-stressed countries, defined as having less than 1,000 m^3 per person per year (Zeb et al., 2011). The per capita availability of water in Pakistan has decreased from 5,300 m^3 in 1951 to less than 1000 m^3 in 2007 due to resource depletion and population pressure (Hussain et al., 2020). It is predicted that the availability of water will be less than 700 m^3 per capita by 2025 (World Bank, 2006). The groundwater and surface runoff are continuously polluted by industrial effluent, raw sewage, storm-water and agricultural leaching.

Pakistan ranks as the seventh most vulnerable country in Asia, predicted to experience long-term drought spells and extreme floods in the future (Hussain et al., 2020; Aslam et al., 2017). Water bodies in the country are contaminated by urban sewage and only a small fraction undergoing treatment before disposal (Asian Development Bank, 2008; WWF, 2007).The situation of water scarcity is expected to worsen with passage of time, particularly in the Indus Basin (WWF, 2007). In certain water-deficient areas, people are already facing the issues due to the unavailability of freshwater, even for drinking purposes (Solomon, 2019). Water scarcity is recognized as a serious threat to natural ecosystem and human health globally (Agarwal et al., 2010; España-Gamboa et al., 2011; Skouteris et al., 2018).

In Pakistan, the beverage industry is one of the key chain of industries. According to estimate, the per capita consumption of soft drinks in Pakistan is approximately 20 liters per annum (Khalid et al., 2019). This industry utilize substantial amount of freshwater and generates large amount of wastewater during washing bottles, drink production, plant wash down, and floor washing. Approximately 3 to 4 liters of freshwater is consumed to produce one liter of soft drink (Nissensohn et al., 2016). Wastewater is largely categorized as two main types (1)

Domestic/municipal and (2) industrial (Chen et al., 2020; Tran et al., 2018). The wastewater composition vary from one to another facility, but there is high pollutant load present, raising concerns about potential adverse effects on human health and aquatic ecosystems (Hidalgo & Martín-Marroquín, 2019). Following industrialization, different industrial units discharge wastewater resulting from various production processes, which vary from one unit to another. Example include wineries, breweries, distilleries, and soft drink manufactures within the food and beverage industry.

The challenge lies in implementing effective methods to treat contaminants in water to mitigate their adverse environmental impact. Water is excessively used in production and processing of soft drinks, about 85 and 95% of water serving as a carrier for the other ingredients (Valero-Cases et al., 2020). Industries often rely on freshwater resources instead of the reuse of waste water resulting in almost 50% of wastewater being utilized in the bottles washing processes in beverage sector (Boguniewicz-Zabłocka et al., 2017). This paper presents a comparative study of wastewater chemistry, highlighting the varying concentrations of ingredients it carries. The composition of wastewater differs from drain to drain as effluent emerges from different processing sections. Typically, the effluents released from beverage industries consist mainly water, sweeteners, flavorings, colorings, carbon dioxide, acidulates, chemical preservatives, sugar, caustic soda, antioxidants and/or foaming agents (Abu-Reidah, 2019).

Guidelines of wastewater treatment and safe disposal, along with their reutilization, remain pivotal factors in promoting sustainable water consumption and maintaining balanced water budget for the food beverage industries (Nasr & Sewilam, 2015; Pham et al., 2016). Recognizing the significance of this issue, the Supreme Court of Pakistan has taken strict action against the excessive use of freshwater in various processes. Regulatory bodies have imposed restrictions on the discharge of hazardous effluent into water bodies to control and minimize the deterioration of water quality. The design and fabrication of wastewater treatment plants (WWTP) are tailored site-specific specifications to achieve the desired quality of effluent discharged into water bodies.

Material and Methods

The Study Area

The study areas selected for this study are situated along the nullah, in industrial estate of Peshawar and Rawalpindi, major cities of Pakistan as depicted in Figure 1**.** Seasonal drainage and primary industrial effluents flow into the nullah, which eventually discharges into nearby water bodies.

Figure 1: Location map of industries.

Sample Collection

Samples were collected from 18 drains location points, originating from various processes units within the industrial estates of both cities. Initial wastewater characterization was conducted in accordance with the National Environmental Quality standards (NEQs) of Pakistan for industrial effluent. The effluent sampling analysis, and flow rate monitoring were carried out at the two different beverage industries. Flow rates and temperatures were measured at various points along different drains, as illustrated in Figure 2. Composite sampling techniques were employed to collect different samples, while flow rates were measured using V-notch techniques and flow meters installed at different locations. The assessment of various physical, chemical and biological parameters was conducted following American Public Health Association/ U.S. Environmental Protection Agency (APHA/US EPA) based standard methods and protocols for wastewater analysis.

Sample Analysis

The wastewater samples underwent thorough characterization and analysis to determine various parameters according to standard methods. The parameters investigated included Biological Oxygen Demand (BOD) at 20℃, Chemical Oxygen Demand (COD), temperature, pH, Total Suspended Solids (TSS), turbidity, Total Dissolved Solids (TDS), Electrical Conductivity (EC), Total Kjeldahl Nitrogen (TKN), Dissolve oxygen (DO), Total Phosphorus (TP), Phosphate (PO_4^{3-}), Iron (Fe), Chloride (Cl^-), and Chromium (Cr). Temperature was measured using a thermometer instrument. TDS and TSS were determined using the

Gravimetric method. BOD_5 at 20℃ for 5 days was analyzed using the Manometric (APHA-5210 D) method, while COD digestion and Colorimetric analysis were performed using APHA-5220 D method.

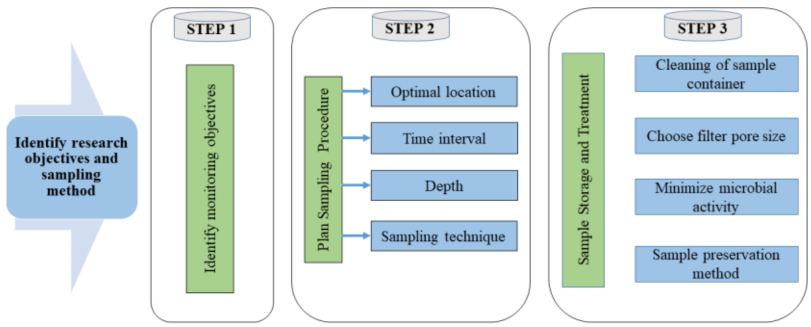

Figure 2: Methodology for sampling of wastewater.

Statistical Analysis

Statistical analysis was employed to evaluate various parameters collected from different location points and assess water quality using different approaches, as outlined by Venkatesharaju et al., (2010). Descriptive statistics, correlation matrix, and Multiple Linear Regression (MLR) analysis were utilized for parameter analysis. To identify and evaluate water quality, Principle Component Analysis (PCA) with Varimax rotation and Kaiser normalization extraction method were employed. PCA is a widely used technique for extracting meaningful information from datasets with multiple variables. By employing these statistical methods, the study aimed to comprehensively assess water quality and identify potential factors contributing to variations observed in the collected data.

Results and Discussion

The beverage industry generates wastewater through many concurrently running processes. Water pollution control can be implemented in each process to reduce both the volume of wastewater and pollution load. Optimization of different processes and integrated techniques can effectively treat wastewater, leading to cost and energy saving. In the beverage industry, the end-of-pipe technique and process optimization have reduced water consumption and pollution load. These techniques are widely practiced in the beverage sector and useful in following aspects, (1) Reduction in water footprints (2) Reduction in wastewater volume (3) Reduction in concentration of pollution load (4) Improvement in water recycling (5) Suitability for water reuse.

The effluent consists of high concentration of BOD and COD, which degrade the quality of water bodies. The preparation of syrup is the most pollution-concentrated process, where microorganisms readily degrade to produce high BOD/mass ratio (Cassano et al., 2015). Generally, untreated effluent from the alcoholic beverage industry including wineries, distilleries and breweries, has the potential to pose environmental hazards. The effluent of soft drinks contains high concentration of nutrient content (nitrogen and phosphorus) due to the chemicals' additives used in the clean-in-place (CIP) units. Therefore, discharging effluent into water bodies without treatment results in eutrophication and salinization of freshwater (Gonzalez-Garcia et al., 2013).

The wastewater consumption ranges from 15000 m^3 to 22000 m^3 per month, varying from season to season. It is estimated that during high seasons (April to August), the plant uses an average of 500-600 m^3 /day. The volume and composition of the wastewater vary according to the units and life cycle of the product, while water losses in the networks range from 60 % -70 %. Some industries practice sustainable models to save water; after initial treatment of effluents from the rinsing process, they can be used for secondary services. Furthermore, the effluent from the fillers can be reused for cooling purposes in different processes within the industry.

Processes in Beverage Industry

In beverage preparation, the production process typically does not involve any hazardous contamination. However, the chemistry of wastewater varies among different industries due to differences in production lines, flavors, syrup and the use of chemicals in boiling and cooling tower. Typically, there are six production lines for beverage preparation and two lines for mineral water. Syrup manufacturing involves mixing sugar with purified water in a pasteurization tank at 65°C, followed by filtration, heating, and cooling processes. As a result, processes may vary from one industry to another, leading to differences in wastewater composition. Activated carbon and filter aids are commonly used to remove impurities, and contents are cooled to below 25°C using cooling tower water. The main processes include the following sections in any beverage industry; (1) Beverage Production Process (2) Water purification (3) Syrup Manufacturing (4) Washing Process (5) Carbon Dioxide Purification (6) Filling Line Process.

The composition of wastewater from industries varies depending on their main processes and production lines. Manufacturing units and their products differ, but there are common units as shown in Figure 3.

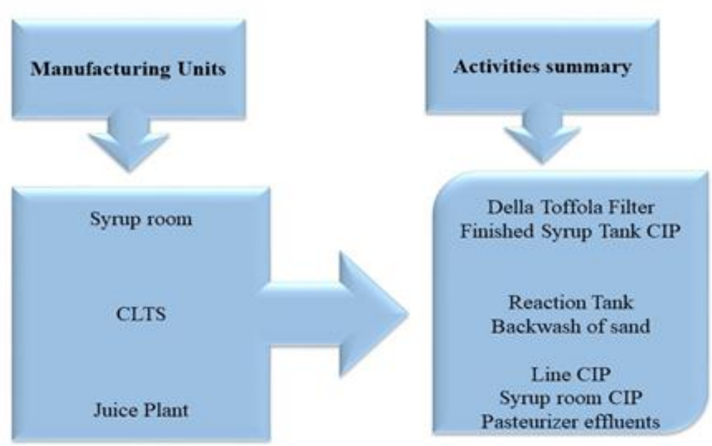

Figure 3: Manufacturing units and their different activities

In the present wastewater analysis, the crucial parameters of the effluents, along with various physicochemical parameters (as shown in the Table 2). The effluent originating from the final bottle washing section has light grey water with an average pH of 7 due to the presence of caustic soda in the solution. Effluent generated from the washing bottle section is diluted with 25-50% freshwater for reuse in different processes. The values of different parameters vary from drain to drain and from industry to industry due to differences in input composition. Descriptive statistical analysis was applied to summarize the values of the two beverage industries from different drains (Table 1).

In addition to the continuing crucial organic load, the effluent also contains high concentrations of oil and grease, ranging from <0.5 to 40 mg/l. The highly fluctuating concentrations of chloride and total hardness contribute to high electrical conductivity (EC) in the wastewater. The concentration of COD fluctuates between a minimum of 12 and a maximum of 10,760 mg/L, with a mean value of 1141.7 mg/l for Industry A. Peak COD values were noted in Industry B, ranging from 25,840 mg/l to a minimum of 374 mg/l, with a mean value of 5405.06 mg/l, which is less than that of Industry A. The variation in wastewater COD and BOD occurs after the cleaning of the bottling line, during which components such as sugars and colors are introduced. Some parameters of the samples at the influent point were analyzed, resulting in 990 mg/l and 1264.75 mg/l for Total Dissolved Solids (TDS) in Industry A and B, respectively. The overall concentration of pollutants in drains from both industries resulted in high concentrations of BOD, COD, and TDS. However, each drain contains high concentrations of BOD, COD, TDS, Total Suspended Solids

(TSS), alkalinity, and chloride, exceeding standard limits. Thus, there is a high concentration of BOD, COD, and TDS present in the effluent.

Table 1: Descriptive statistical analysis of different parameters.

Parameters		Minimum	Maximum	Mean	Std. Deviation
pH		4	12	7.13	2.363
BOD		3	5056	468.13	1249.17
COD		12	10760	1141.75	2671.84
TDS	Industry A	291	3072	990.00	742.46
TSS		7	1796	236.94	472.31
Alkalinity		60	1340	505.63	455.54
OG		2	5	3.63	0.80
TKN		3	5	4.00	0.82
Chloride		39	734	117.94	166.39
pH	Industry B	3.95	12.14	7.71	3.39
BOD		119	8164	1722.31	1910.99
COD		374	25840	5405.06	6045.54
TDS		85	4010	1264.75	1340.03
TSS		17	806	184.94	226.59
Alkalinity		40.0	2020.0	669.91	637.72
OG		3.50	48.00	19.83	14.38
TKN		1.41	4.56	3.29	1.09
Chloride		35.22	1712.00	191.75	407.52

Note: pH = the measure of acidic/basic nature, BOD=Biological Oxygen demand at 20 ^{0}C for 5 days, COD= Chemical Oxygen Demand, TDS= Total Dissolve Solids, TSS=Total Suspended Solids, Alkalinity= Buffering capacity of in basic pH range, OG=Oil & Grease, TKN= Total Kjeldahl Nitrogen.

In Table 2, different variables of wastewater are presented in a correlation matrix, which is applied to evaluate the dissolved oxygen in water bodies. The quality of water is determined by decreasing levels of dissolved oxygen due to contamination. Thirupathaiah et al. (2012) developed a methodology for finding the correlation between different parameters, While Chenini & Khemiri (2009) successfully applied multiple linear regression for Evaluating groundwater quality. Performing factor analysis aims to reduce data variability through two methods: Factor Extraction and Factor Rotation. After extracting the desired number of factors, the next step is to interpret factor loadings. The factor or component matrix for each element is computed, and the square loadings are calculated. For instance, if the cumulative square loadings for the factors are 23.7%, 43.5%, and 58.5%, respectively, the total sum of the square loading values of the factor matrix provides the communalities for each item in the extraction method of PCA. Rotated component matrix of different wastewater parameters are shown in Figure 4.

Table 2: Correlation Matrix of industry A and B

	pH (A)	BOD (A)	COD (A)	TDS (A)	TSS (A)	Alkalinity (A)	OG (A)	TKN (A)	Chloride (A)	pH (B)	BOD (B)	COD (B)	TDS (B)	TSS (B)	Alkalinity (B)	OG (B)	TKN (B)	Chloride (B)
pH (A)	1.00	-0.38	-0.38	0.48	-0.19	0.09	0.20	-0.31	0.02	-0.32	-0.20	-0.20	-0.26	0.08	-0.30	0.42	0.23	-0.01
BOD (A)	-0.38	1.00	1.00	-0.16	-0.09	-0.13	-0.27	0.04	-0.12	0.34	-0.21	-0.21	0.36	-0.24	0.52	0.06	0.22	-0.12
COD (A)	-0.38	1.00	1.00	-0.13	-0.07	-0.07	-0.29	0.05	-0.13	0.34	-0.20	-0.20	0.34	-0.26	0.49	0.06	0.23	-0.13
TDS (A)	0.48	-0.16	-0.13	1.00	-0.01	0.34	-0.09	-0.17	0.34	-0.09	-0.27	-0.27	0.05	0.15	-0.18	0.36	0.04	0.27
TSS (A)	-0.19	-0.09	-0.07	-0.01	1.00	0.74	-0.26	-0.04	-0.15	-0.42	-0.08	-0.08	-0.34	-0.08	-0.36	-0.07	-0.23	-0.14
Alkalinity (A)	0.09	-0.13	-0.07	0.34	0.74	1.00	-0.29	-0.03	-0.22	-0.43	-0.08	-0.08	-0.43	-0.06	-0.50	0.22	-0.06	-0.21
OG (A)	0.20	-0.27	-0.29	-0.09	-0.26	-0.29	1.00	-0.10	-0.16	0.01	-0.13	-0.13	-0.11	0.02	0.03	0.12	-0.17	-0.19
TKN (A)	-0.31	0.04	0.05	-0.17	-0.04	-0.03	-0.10	1.00	0.25	0.13	0.42	0.42	-0.03	0.22	-0.24	-0.03	0.13	0.27
Chloride (A)	0.02	-0.12	-0.13	0.34	-0.15	-0.22	-0.16	0.25	1.00	0.34	-0.20	-0.20	0.61	0.72	0.16	-0.07	-0.16	0.99
pH (B)	-0.32	0.34	0.34	-0.09	-0.42	-0.43	0.01	0.13	0.34	1.00	-0.12	-0.11	0.81	-0.03	0.81	-0.51	0.26	0.31
BOD (B)	-0.20	-0.21	-0.20	-0.27	-0.08	-0.08	-0.13	0.42	-0.20	-0.12	1.00	1.00	-0.40	-0.14	-0.39	-0.06	0.13	-0.18
COD (B)	-0.20	-0.21	-0.20	-0.27	-0.08	-0.08	-0.13	0.42	-0.20	-0.11	1.00	1.00	-0.40	-0.14	-0.38	-0.07	0.13	-0.17
TDS (B)	-0.26	0.36	0.34	0.05	-0.34	-0.43	-0.11	-0.03	0.61	0.81	-0.40	-0.40	1.00	0.30	0.86	-0.26	0.15	0.59
TSS (B)	0.08	-0.24	-0.26	0.15	-0.08	-0.06	0.02	0.22	0.72	-0.03	-0.14	-0.14	0.30	1.00	-0.03	0.36	-0.31	0.75
Alkalinity (B)	-0.30	0.52	0.49	-0.18	-0.36	-0.50	0.03	-0.24	0.16	0.81	-0.39	-0.38	0.86	-0.03	1.00	-0.27	0.20	0.14
OG (B)	0.42	0.06	0.06	0.36	-0.07	0.22	0.12	-0.03	-0.07	-0.51	-0.06	-0.07	-0.26	0.36	-0.27	1.00	0.06	-0.06
TKN (B)	0.23	0.22	0.23	0.04	-0.23	-0.06	-0.17	0.13	-0.16	0.26	0.13	0.13	0.15	-0.31	0.20	0.06	1.00	-0.22
Chloride (B)	-0.01	-0.12	-0.13	0.27	-0.14	-0.21	-0.19	0.27	0.99	0.31	-0.18	-0.17	0.59	0.75	0.14	-0.06	-0.22	1.00

Note: This matrix is not positive definite.

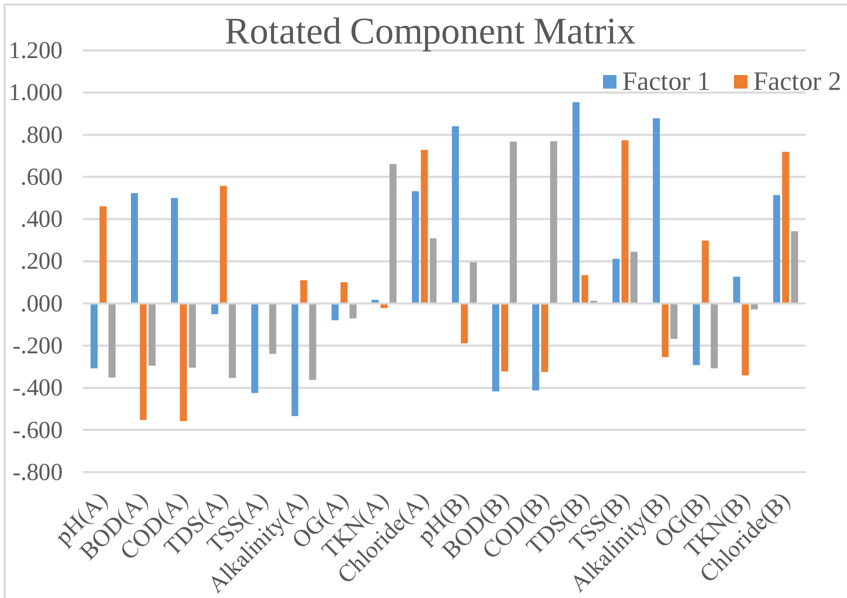

Figure 4: Rotated component matrix of different wastewater parameters.

Table 3 presents the simple structure of three factors, with the factor matrix obtained through factor transformation matrix and the calculated rotated factor matrix. Component loadings, which represent the correlations between the variable and component, range between -1 to +1.

In general, a limited amount of total phosphate and nitrogen concentration was observed in the effluent, indicating the potential to cause eutrophication (Nandakumar et al., 2019; Pham & Bui, 2020). The high concentration of nutrients increases the levels of BOD and COD, with organic pollutants adversely affecting aquatic life, especially fishes. Additionally, high levels of chloride, nitrogen, and phosphorous contributes to toxicity in the environment.

Table 3: Component Transformation Matrix

Component	1	2	3
1	0.893	0.343	0.29
2	-0.424	0.857	0.292
3	0.148	0.384	-0.911

Extraction Method: Principal Component Analysis (PCA).
Rotation Method: Varimax with Kaiser Normalization.

Treatment of Wastewater

In food and beverages industries, wastewater treatment holds paramount importance for (1) water recycling, (2) resource recovery, and

(3) environmental protection. The presence of chemical and biological pollutants has necessitated the development of treatment methods with high removal efficiency membranes. The Maximum Permissible Amount (MPA) for COD and BOD to be discharged into resources is 120 and 40 $mg \cdot L^{-1}$, respectively. However, the composition of soft drink processing wastewaters has been reported to be 20 times higher than the MPA. Biological treatment technologies are widely used to mitigate environment impact against high levels of COD and BOD.

On the other hand, wastewater from non-alcoholic beverage industries contains pollutants such as sugar and starches, product mixes and concentrates, cleaning chemicals, sugars, pectin, coloring, and flavoring additives (Agana et al., 2013; Haroon et al., 2013). The effluent discharged from various units and operations is stored in an equalizing tank for mixing acidic and basic effluent before undergoing aerobic and anaerobic processes prior to discharge into the municipal sewer. The process flow for wastewater treatment is shown in Figure 5.

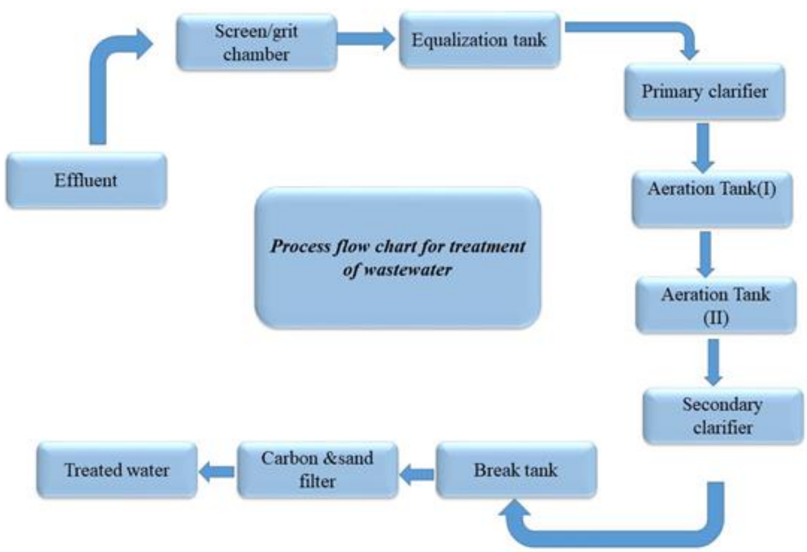

Figure 5: Process flow diagram of WWTP

In a typical WWTP setup, effluent from different drains is collected and mixed in an equalization tank, where chemical dosing for automatic reagent injection into the wastewater network occurs. The effluent then passes through a screen/grit chamber before being transferred to recirculation pumps, with water fed to a primary clarifier following chemical dosing from the equalization tank to balance pH and flow. Subsequently, water from the primary clarifier enters aeration tanks I and II, secondary clarifiers, and a break tank. A Moving Bed Biofilm Reactor

(MBBR) is a filtration system known for effectively removing organic and inorganic contaminants from wastewater (Bouhadjar et al., 2012). MBBR-based systems are equipped with gauges and controls to enable operators to run and monitor them smoothly. Moreover, MBBR systems offer flexibility, as they can be installed in aerobic and anaerobic tanks within the WWTP (Sikosana et al., 2019; Yan et al., 2021). Once treated in the break tank, water is fed to a multimedia filter through a feed pump for carbon and sand filtration to reduce the concentration of total dissolved solids before disposal. Sludge collected in sludge holding tanks from primary and secondary clarifiers is fed to a filter press via a diaphragm pump. In the filter press, sludge cake is formed, and sludge wastewater is recirculated in the equalization tank, as depicted in Figure 6.

The National Environment Policy outlines the mandate to protect, conserve and restore Pakistan's environment to enhance the citizens' quality of life through sustainable development. The policy emphasizes three main objectives: (1) Conservation, (2) restoration and (3) efficient management of natural resources. According to the National Environmental Quality Standards (Self-Monitoring and Reporting by Industry) Rules, 2001, industrial units are classified into categories "A", "B", or "C" for liquid effluents based on their pollution levels. Additionally, gaseous emissions are classified into categories "A" or "B". Industrial units categorized as "C" are required to submit Environmental Monitoring Reports (EMRs) biannually for priority parameters related to liquid effluents listed in Schedule V. Beverage industries fall under category C and must focus on liquid effluent management while submitting EMRs for the specified parameters biannually.

The modern beverages industry emphasizes sustainable and environmentally friendly management systems, including water resource conservation, water recycling and reuse, reduction in wastewater volume, and the implementation of waste minimization techniques (European Commission, 2017). To ensure the adoption of sustainability in beverage industries, all stages from raw material supply to beverage processing, preparation, packaging, transportation, distribution, and disposal must be based on sustainable manufacturing principles and clean technologies. Production and processing practices should incorporate environmental technologies to mitigate environmental impacts. Additionally, life cycle assessments of processes should be based on closed-loop systems to minimize water and energy flow out of the system.

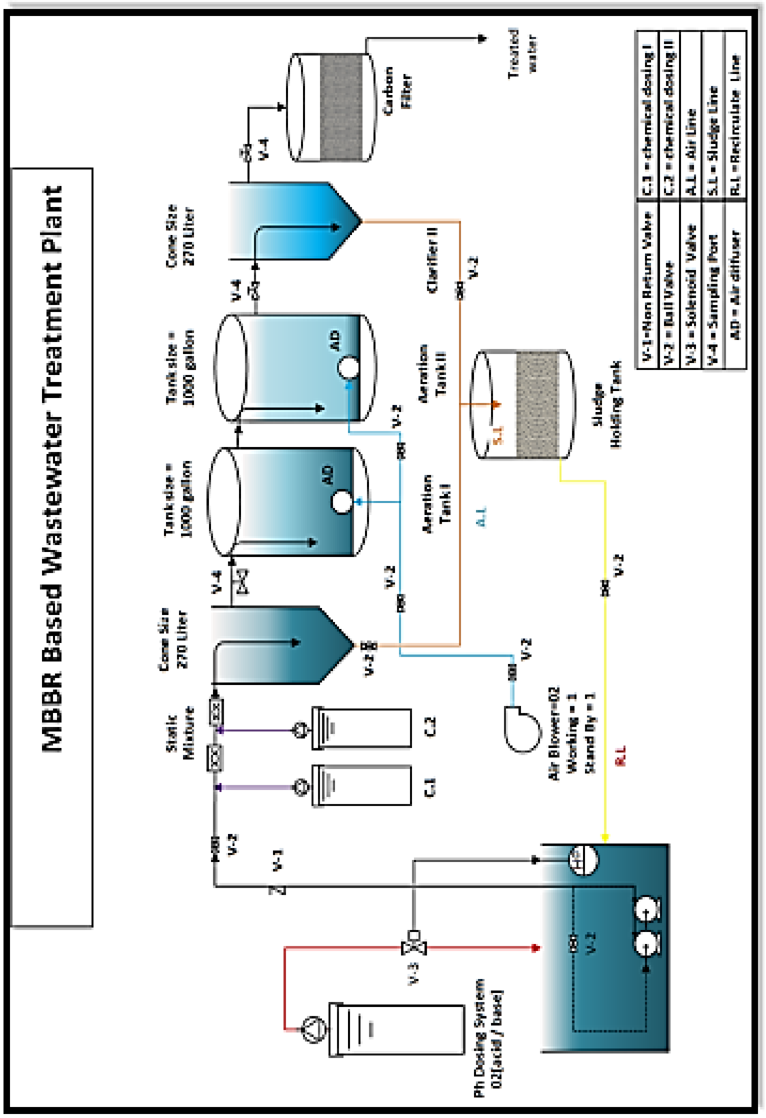

Figure 6: MBBR based wastewater treatment plant National Environmental policy related to Beverage industry.

Wastewater Reuse and Management

In novel approaches of circular economy, the consumption and management of water can facilitate resource recovery (Narasimmalu & Ramasamy, 2020). Globally, approximately 200 million farmers irrigate and produce market-oriented crops, such as vegetables, pulses, cereals, and oilseeds, using raw wastewater. Although there are many benefits and environmental hazards associated with irrigation through wastewater. In many water-stressed areas, treated wastewater is utilized to improve ponds, urban lakes, wetlands, and other wildlife habitats. Organic matter, nutrients, and other carbon-based materials may increase crop yields, whereas continuous irrigation with wastewater may disturb soil microbes and physicochemical soil properties (Christou et al., 2017). As a result, it deteriorates land fertility, crop yield, and productivity. Irrigation through wastewater facilitates the transfer of heavy metals from soil to the vegetation part of plants, ultimately accumulating them, which is influenced by soil characteristics (pH, texture, and cation-exchange capacity) and crop physiology (type, root secretions, surface area, and transpiration).

Both qualitative and quantitative data are utilized for the application of water management including process (1) water requirement of different units (2) operational flow diagram, (3) qualitative characteristics of wastewater and key contaminants, (4) volume of generated wastewater (5) qualitative characteristics of water and (6) feasibility of wastewater treatment. An integrated water system is suggested for the food and beverage sectors due to high potential of water consumption and wastewater discharge. These systems are interconnected among water utilization, management, environmental and resource protection with sustainable food production, using water-food-environment nexus.

In water-stressed areas, recycled wastewater can mitigate the adverse environmental impacts by providing a continuous water supply to agricultural lands, thereby improving crop production (Qadir & Scott, 2009). After initial treatment, the reuse of recycled wastewater could significantly reduce runoff into surrounding areas (Hong et al., 2018). Recycled wastewater plays a significant role in freshwater consumption management, wastewater minimization and sustainable food production by reducing environmental footprints (Drangert et al., 2018). However, many scientists have reported that the long-term risks to human health and environment are unknown, especially in small land agriculture scenario. Long-term irrigation with wastewater can lead to adverse effects through the gradual accumulation of toxic metals. Contamination in food crops and land, vulnerable to bioaccumulation, can affect the ecosystem and human health (Qureshi et al., 2016; Zhang & Shen, 2019).

A significant amount of nutrients such as nitrogen, phosphorus, and potassium (NPK) act as fertilizers when crops are irrigated with recycled wastewater. This facilitates the metabolic action of microorganisms at the soil-plant interface, resulting in remarkable yields and straw production compared to groundwater irrigation. Additionally, irrigation with partially or untreated wastewater improves agricultural production, reduces the need for fertilizers, promotes nutrient recycling, conserves freshwater resources, and provides economic support to farmers (Libutti et al., 2018). However, wastewater irrigation also poses severe health hazards due to the gradual contamination of land, crops, and groundwater with toxic metals and microbial pathogens. Pathogenic contamination from wastewater irrigation can lead to health hazards for farmers (Meli et al., 2002).

Conclusion

Freshwater resources are depleting rapidly due to poor management practices on a large scale. Freshwater is a fundamental necessity for life and the primary source of drinking water. Urgent action is needed to address this issue by reusing and recycling domestic and non-hazardous industrial wastewater, thereby alleviating the pressure and demand for fresh water. Wastewater from the food and beverage sector contains sugars, flavors, and color additives, leading to high levels of BOD and COD, which in turn decrease the dissolved oxygen in water bodies. Given the large volume of wastewater generated during various processing units in the food and beverage sector, it is highly recommended to reuse treated effluent after initial wastewater treatment using efficient technologies to reduce the organic load.

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