Local Wastewater Treatment Plant for Dairy Production: Challenges and Solutions

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Abstract. Main factors that can negatively affect the operation of wastewater treatment plant for dairy production were identified. The main negative factors are: low automation of the process, high concentrations of chemical reagents that have a detrimental effect on the biological treatment stage, temporary fluctuations in pH values, insufficient amount of dissolved oxygen at the biological treatment stage. One of the main operation problems of local dairy wastewater treatment plant is a fluctuation of pH value over a wide range, especially at treatment plants of small enterprises. Biological treatment methods were considered as one of the most suitable technologies for the removal of organic substances from dairy wastewater. It was concluded that there are quite stringent conditions for each treatment stage. The pH range is almost neutral and fluctuate within 6-8.5. The average temperature of wastewater should be 20-30°C for optimal biochemical reactions. The concentration of dissolved oxygen plays an overriding concern for biological treatment stage, since good operation of processes of nitrification, denitrification and biological phosphorus removal are based on this indicator and will not proceed in case of deviations from the normal.

1. Introduction

Nowadays, there are about 7.8 billion people in the world, and the demographic growth rate at the beginning of 2021 is about 1.25% [1]. Along with the increase in the number of people in the world, food production is also increasing, which leads to the development of the food industry [2].

Therefore, dairy industry occupies an important niche, as it serves as a source of valuable food products. It can be drawn from statistics: in 2020 alone, consumption of dairy products in Russia increased by 3% to 29.3 million tons of products produced by dairy industrial enterprises. In addition to large industrial enterprises, there is a huge number of small enterprises and farms. Their emergence is due to the high demand for dairy products, both in our country and around the world as a whole [3].

One of the biggest environmental problems of dairy production is wastewater. Dairy industrial wastewater entering the environment can have a negative impact on the local biocenosis of water body and soil, due to the high content of organic substances and specific bacteria (most commonly Lactic acid bacteria), as well as high phosphate and fat content, which leads to disruption of natural processes [4,5].
In accordance with Sanitary Regulations and Norms 2.3.4.551-96 "Production of milk and dairy products," measures prevented environmental pollution should be provided at dairy processing enterprises due to the discharge of flushing wastewater containing fats and protein waste, chemicals, disinfectants, and detergents, etc. [6].

However, there are mandatory standards that apply to all dairy processing enterprises. In accordance with Article 5, Chapter 1 of the Federal Law № 416 "On Water Supply and Sanitation", as well as taking into account the requirements of industrial wastewater discharge into the city sewerage, it became necessary to have local dairy wastewater treatment plant at the enterprise [7,8,9,10].

The local dairy wastewater treatment plant includes different stages: mechanical, physico-chemical, biological and post-treatment stage. It is worth noting that physical-chemical stage and the post-treatment stage are optional and are installed with the recommendation of specialists [5].

Indeed, it is more difficult to establish the operation of wastewater treatment plants at small enterprises than at large. It is related to the fact that it is much easier to operate fluctuations of wastewater composition at large enterprises, primarily due to the averaging of the incoming effluent in a contact tank. An important factor for the proper operation of wastewater treatment plants at small enterprise, is the correct automation of process, which requires constant monitoring by specialists [5]. Although, it increases operation and maintenance costs of wastewater treatment plant. Also, a number of difficulties are related to the higher concentration of chemical reagents used for flushing equipment, which has a detrimental effect on the biological (biochemical) [11,12,13].

2. Materials and methods
Wastewater of the dairy industry have their own characteristics, but at the same time they are individual for each processing enterprises, since they each produce different products from different raw materials [14]. In dairy production, wastewater is produced by various processes, as a result, contaminants also are different. Main technological processes of dairy production, where contaminated wastewaters are formed [14]:

- Production of curd, cheese and other dairy products.
- Reconstitution of milk powder.
- Cooling of milk and dairy products.
- Flushing of process equipment, containers and pipelines.
- Operation of technological and steam installations.
- Household needs.
- Washing of floors and panels at processing enterprises.

It is worth noting that the above processes can be divided into two types: process water that has contact with manufactured product process water for additional processes [13,14]. Flushing water generates in the largest quantity and significantly differs in composition from wastewater from main technological processes, mostly by alkaline reagents.

Dairy wastewater is water with a complex of substances, containing colloidal dispersions (caseins, albumin, globulins, enzymes), emulsified fats as triglyceride mixture, free fatty acids, suspended (mineral or organic matter) [15] and dissolved particles of organic matter pollutants, which are reflected by BOD and COD indicators [13]. In addition, important parameters of wastewater are temperature, hydrogen index (pH), chromaticity, bacteriological index (normalizes the content of bacteria such as E. coli and pathogenic microorganisms in water) [16,17], concentration of organic and mineral substances. The main pollutants in wastewater from dairy production, as shown in Table 1 and Figure 1, are suspended solids, COD, BOD, fat, chlorides, ammonia nitrogen and others [18].
Table 1. Wastewater characteristics from dairy production and household [11,18-25].

| Components            | Dairy plant effluent | Domestic wastewater |
|-----------------------|----------------------|---------------------|
| Suspended solids, mg/l| 350-1500             | 140-300             |
| pH                    | 4-12                 | 6-9                 |
| COD, mg/l             | 5000                 | 250-500             |
| BOD, mg/l             | 3000                 | 180-300             |
| Ammonia nitrogen, mg/l| 20-60                | 35                  |
| Total phosphates, mg/l| 8-80                 | 4.5-8               |
| Fats, mg/l            | 350-700              | 40-50               |
| Chlorides, mg/l       | 150-200              | 45                  |
| Sulphate, mg/l        | 124.0-186.0          | 650                 |
| Calcium, mg/l         | 40-85                | 79                  |
| Magnesium, mg/l       | 10-20                | 120                 |

Figure 1. Comparison diagram of wastewater characteristics from dairy production and household [11,18-25].

The diagram shows wastewater characteristics from dairy production and household. As can be seen in the diagram, the values of suspended solids, pH, COD, BOD, ammonia nitrogen, total phosphates, fats, chlorides, and calcium in dairy wastewater exceed these values in domestic wastewater. At the same time, sulphate values are higher in domestic wastewater as a result of the ingress of large amounts of detergents in the wastewater.

It is worth noting that due to the specific nature of produced products, dairy wastewater is characterised by an increased content of proteins, fats, and carbohydrates, resulting in a fairly rapid process of souring and decay. Lactic acid is formed during the digestion of lactic sugar and this subsequently leads to the precipitation of protein substances such as casein, which can severely disrupt the operation of wastewater treatment plants [14,18].

One of the main operation problems of local dairy wastewater treatment plant is a fluctuation of pH value over a wide range, especially at treatment plants of small enterprises. The pH value of wastewater will depend on the range of produced products (cheese, milk, curd, etc.) as well as...
production technology. If there are no acidic products, wastewater pH will vary within a neutral or slightly alkaline environment (pH = 6.5-8.5) [18]. Where dairy products are produced, the pH of the wastewater varies between neutral and slightly acidic (pH = 5.5-7.5), but sometimes reaches quite low level (pH = 2-3) [5,13]. This low pH value is observed in the case of a single line producing dairy products at specific times. Whereas at large plant it is possible to operate several process lines so that incoming wastewater from each line with different pH values is mixed and pH of wastewater is equalized without chemicals addition, at small plant additional reagents cannot be avoided.

Local dairy wastewater treatment plant with small capacity is characterized by irregularity in both volume and quality composition throughout day and week. The volume of incoming wastewater depends on the amount of processed milk, type of product (curd, cheese) and equipment, production method, control system and washing mechanism [14]. In addition, the volume and quality composition of the wastewater varies throughout the year due to changes in the diet of livestock and, consequently, in the composition of products themselves [12].

Other components of dairy wastewater, as mentioned above, are reagents used to equipment flush. An important aspect is manual washing, which is often used at wastewater treatment plants with small capacity. Alkaline reagents used to completely remove contaminants from the equipment is not controlled and may exceed the prescribed limits. Thus, when washing equipment, inorganic substances used as reagents (alkalis, acids) introduce to wastewater, that leads to a violation of the biological treatment stage (starvation of microorganisms) and, in some cases, the complete death of microorganisms or biocenosis change, which will not be able to clean the incoming wastewater.

3. Results and discussion

In order to treat dairy wastewater at local wastewater treatment plant and to meet hygienic requirements for water body depending on the type of water use [26,27], the following sequence of treatment methods should be applied (Figure 2): mechanical treatment unit (grids, grease traps), physical and chemical treatment unit (coagulation, flotation) as well as biological (biochemical) treatment unit and post-treatment unit (filtration and disinfection stage). Wastewater treatment methods and techniques should be determined taking into account local conditions, depending on the composition of the wastewater and the requirements for the discharge indicators.

![Figure 2. Treatment processes at dairy wastewater treatment plant.](image-url)

Biological treatment methods can be considered as one of the most suitable technologies for the removal of organic substances from dairy wastewater, due to their high degree of biodegradability [13]. Biological wastewater treatment is the conversion of colloidal and dissolved organic matter into mineral compounds through the activity of bacteria. Moreover, biological treatment processes are
similar to self-purification processes in natural water bodies, intensified by the use of engineering systems (e.g., aeration tanks and digesters) [12,17]. However, before the wastewater reaches the biological treatment stage, it must undergo a mandatory mechanical treatment stage. This is necessary to prevent the sewage pipes from becoming clogged with waste and to avoid the breakdown of the subsequent process equipment (especially pumps). The mechanical treatment consists of various devices (grids, sand traps, grease traps, etc.). A mechanical screen is installed at the first stage of local wastewater treatment plant. When designing local dairy wastewater treatment plants, as a rule, drum screens with a perforated fabric and a small gap (1-3 mm) are used, as in such wastewater will not have large inclusions that can damage this equipment. The use of a grease trap designed to separate fat impurities from the effluent is not always justified at local dairy wastewater treatment plant due to the low-fat content (about 20-30 mg/l) [29].

The next step is physical-chemical treatment, which is represented by flotation with coagulation. These processes are necessary in the case of high-fat levels of (more than 300 mg/l), which are left in the effluent after mechanical treatment. This step is also mandatory in the case of discharge of whey, which is a useful secondary raw material for the production of baby food and sports nutrition [11].

The whey realization is a big problem in a small dairy enterprise. This is primarily due to the high costs of transporting a small amount of whey. Moreover, the alternative production of dry powder from whey directly at the enterprise also requires large capital investments and operating costs [13]. Therefore, whey is discharged into the sewerage and go to treatment plant. As a result, it can lead to disruption of the main treatment stage at dairy wastewater treatment plant – biological. This is due to high levels of nitrogen- and phosphorus-containing compounds in whey, which can lead to an increase in the number of filamentous bacteria, inhibition biochemical processes or even death of activated sludge (biocenosis) [29,30].

Flotation is wastewater treatment process for reducing fats, suspended solids and surfactants concentration using air bubbles. The larger the surface of the bubbles and the contact area with solid particles, the more effective process will be. Before wastewater enters the flotation unit, a coagulant is added by a reagent dosing unit. The resulting flotation sludge (float) is removed from the surface using a rake mechanism. Then flotation sludge enters the sludge collector tank and is removed from there for subsequent processing [29,31]. Unfortunately, flotation process in small enterprises is often completely absent due to the small volume of wastewater and high cost of equipment and its operation. In addition, implementation of flotation process is not always reasonable due to relatively low concentrations of COD, BOD and fats at dairy wastewater treatment plants [31].

Unequal flowing wastewater with inhomogeneous composition from the enterprise before flotation unit enters a blending tank, where wastewater is subjected to a neutralization process with acids or alkalis depending on the pH value. Afterwards, they enter the flotation unit or, in the absence of physicochemical treatment stage, to biological treatment stage [32].

As mentioned earlier, operation of small local dairy wastewater treatment plant is more difficult than wastewater treatment plant at large enterprise. It is associated with characteristic properties, flowing wastewater, its composition and requirement for proper automation. After passing through mechanical treatment and flotation (optionally) wastewater flows to biological treatment stage. This stage is the main one at local dairy wastewater treatment plant. This stage is necessary due to the high content of organic substances, typical for the effluents of the dairy industry [28].

The main equipment at biological treatment stage is an aeration tank [33]. It is a represented concrete or steel tank where a continuous air supply is carried out in order to maintain the nitrification process. As wastewater is saturated with oxygen, intensive processes of mineralization and oxidation of suspended, colloidal and dissolved substances occur. Therewith, activated sludge is formed, which, together with the treated water enters the secondary settling tank [34]. It is also important to organize an anoxide treatment (denitrification) zone in the aeration tank by stopping the air supply or placing wastewater in the oxygen deficiency zone. Denitrification is an anaerobic process with a lack of oxygen, during which the circulating nitrate (NO3) in the tank is reduced to pure nitrogen (N2). Thus, due to the organization of nitrification and denitrification processes, wastewater undergoes a full cycle.
of treatment from nitrogen-containing compounds, therefore, COD and BOD indicators are also reduced [28].

Moreover, at biological treatment stage there is one more process – biological phosphorus removal. Most commonly, in the dairy industry, phosphorous concentration is low (approximately 5-16 mg/l) [35]. However, actual values can reach 52.3 mg/l [36]. In this case, there is a need for anaerobic biological treatment. During the anaerobic process, microorganisms (phosphorus-accumulating organisms), falling into a shock state, due to a lack of oxygen and an excess of food. They begin to actively release phosphorus from cells in order to survive in such conditions, providing themselves with the necessary energy supply. Then, when it enters aerobic conditions (nitrification stage), the accumulated energy is released, and inorganic phosphorus is assimilated in the biological cell and stored in the form of polyphosphate inclusions. Phosphorus-storing organisms absorb more phosphorus under aerobic conditions than excreted under anaerobic conditions. As a result, the concentration of phosphorus in phosphorus-accumulating organisms increases, while phosphorus concentration in wastewater decreases [17,37].

For each stage of dairy wastewater treatment, the pH value is important, which itself is extremely unstable at different periods of time in the enterprise. Chemical reagents are used to regulate this parameter at different stages. Initially, reagents enter runoff with household sewerage and flushing water for processing equipment, containers and pipelines. Fore-mention chemical reagents negatively affect the biocenosis of biological treatment stage and can lead to its swelling. Sludge swelling can also be the result of death of organisms and growth of other microorganisms (for example, filamentous bacteria) in this environment that are unable to treat [28,38].

After secondary clarifier, wastewater undergoes an additional treatment stage, represented by filtration units (for example, sand filtration) to filtrate the remaining contaminants (flocs of activated sludge). The final stage of local dairy wastewater treatment plant before their will be discharged takes place in a contact tank. The process of wastewater disinfection with ultraviolet irradiation, chlorine or ozone takes place here [13]. Chlorination is often used, but the most modern method disinfection is ultraviolet irradiation. Disinfection is a mandatory step for local dairy wastewater treatment plant due to the high microbiological activity of wastewater [34].

After passing through all treatment stages, effluent must comply with the standards for discharge into fishery water bodies [27], or to the centralization sewerage in accordance with Government regulations of Russian Federation of 05/22/2020 No. 728 [39]. In the case of effluent discharge into water body, an additional above-mentioned post-treatment stage is required. For discharge to the centralization sewerage, there is no need for this stage because wastewater will be treated on centralized wastewater treatment plant.

Table 2. Necessary conditions for some stage operation on local wastewater treatment plant for dairy production [11,40].

| Conditions       | Flotation     | Nitrification | Denitrification | Biological phosphorous removal |
|------------------|---------------|---------------|-----------------|-------------------------------|
| pH               | 6.0-8.0       | 7.5-8.5       | 7.0-8.5         | 7.0-8.0                       |
| Temperature      | <60ºC         | 10-30ºC       | 5-30ºC          | 30-35º                        |
| Dissolved oxygen | Have no affect | >1.0 mg/l     | Low concentration| Absence of oxygen             |

It is worth pointing out a number of limitations, due to which this or that stage on local wastewater treatment plant may not function. For proper operation, it is necessary to maintain certain conditions
(pH, temperature, dissolved oxygen concentration), the most stringent among them are for nitrification, denitrification and flotation processes, which are shown in Table 2.

Based on the data in the table, it was concluded that there are quite stringent conditions for each treatment stage. The pH range is almost neutral and fluctuate within 6-8.5. At the same time, the average temperature of wastewater should be 20-30ºC for optimal biochemical reactions. The concentration of dissolved oxygen plays an overriding concern for biological treatment stage, since good operation of processes of nitrification, denitrification and biological phosphorus removal are based on this indicator and will not proceed in case of deviations from the normal. However, this indicator does not affect the flotation process.

In addition, an important indicator of optimal operation for biological treatment stage is the sludge load. A high sludge load is considered to be > 400 mg BOD$_{total}$ per 1 gram of ashless active sludge per day [28,38]. At such wastewater treatment plants, there are maximal sludge growth and the least purification rate. Activated sludge with high load cannot oxidize incoming contaminants. Under these conditions, filamentous bacteria can develop, sludge flakes disintegrate, large numbers of bacteria are present in suspension, and the water above the sludge is turbid [41].

Moreover, it is necessary to control optimal parameters sludge volume index (SVI) and main nutrients demand during operation. SVI is maintained at 2-3 g/cm$^3$. An increase in SVI would accelerate oxidative processes, but problems arise when separating sludge in secondary clarifiers [38]. For the present, there are technologies that allow maintaining SVI at 6-12 g/cm$^3$, while the operation of secondary clarifiers is not disturbed. Main nutrients demand is usually estimated by the ratio of BOD$_{total}$:N:P, which should be 100:5:1 as optimal. In this ratio nitrogen in ammonium salts or protein nitrogen and phosphorus in the form of soluble phosphates are taken into account. [17,28].

4. Conclusions
As a result of the research performed, main factors that can negatively affect the operation of wastewater treatment plant for dairy production were identified. The main negative factors are: low automation of the process, high concentrations of chemical reagents that have a detrimental effect on the biological treatment stage, temporary fluctuations in pH values, insufficient amount of dissolved oxygen at the biological treatment stage.

If the operating conditions of dairy wastewater treatment plants are met, as well as there were involving or modernizing auxiliary technological stages (for example, involving a stage for reagents addition to equalize pH of wastewater, increasing air flow for oxygen supply to the biological treatment stage or replacing biological treatment technologies with more efficient), it is possible to treat incoming wastewater up to regulatory limit of discharge into the water bodies and reducing the negative impact on it.

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