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Integration of Failure Mode and Effects Analysis and Full-Scale Treatment Plant Monitoring for the Management of Dairy Wastewater: Evidence from a Case Study

Marco Carnevale Miino · Vincenzo Torretta · Jan Vespalec · Martina Repková · Petr Hlavínek · Julius Telek

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Abstract Dairy wastewater (DWW) contains very high levels of fats and oils (FAO), organic compounds, and other nutrients. These components pose a danger to the biological processes of wastewater treatment plant (WWTP) and may also affect the effluent's quality. This study focuses on the combined approach of conventional Failure Mode and Effects Analysis (FMEA) and monitoring of a WWTP treating mainly DWW. After some actions were implemented to reduce the risk, the qualitative variation of the DWW was assessed and FMEA has been updated. The results highlighted that the WWTP has lower performance on organic matter than expected probably due to the low biodegradability of wastewater and the high concentration of FAO that could have limited the diffusion of oxygen in the bioreactor. However, this last aspect remains speculative and warrants further investigation to exclude other causes. The actions implemented after the FMEA help to limit the identified risks and reduces the amount of FAO discharged from the factory by 39.5%. These findings can be beneficial for both the scientific community and technical operators, highlighting the importance of integrating FMEA with large-scale WWTP monitoring and providing useful information for the management and treatment of industrial wastewater, not limited to the dairy sector.

Keywords Dairy wastewater · Biological treatment · Industrial wastewater · Plant efficiency · FMEA

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M. Carnevale Miino (✉) · V. Torretta
Department of Theoretical and Applied Sciences,
University of Insubria, Via O. Rossi 9, 21100 Varese, Italy
e-mail: marco.carnevalemiino@uninsubria.it

V. Torretta
e-mail: vincenzo.torretta@uninsubria.it

J. Vespalec · M. Repková · J. Telek
Institute of Chemistry and Technology of Environmental
Protection, Faculty of Chemistry, Brno University
of Technology, Purkyňova 464/118, 612 00 Brno,
Czech Republic
e-mail: jan.vespalec@vut.cz

M. Repková
e-mail: repkova@fch.vut.cz

J. Telek
e-mail: telekjulius@gmail.com

P. Hlavínek
AdMaS Research Center, Faculty of Civil Engineering,
Brno University of Technology, Purkyňova 651/139,
612 00 Brno, Czech Republic
e-mail: petr.hlavinek@vut.cz

1 Introduction

Industrial progress positively influences the global economy. However, economic development also has negative consequences for society, as industrialization is associated with the need for a significant amount of water and environmental contamination of aquatic and terrestrial ecosystems (Ahmad et al., 2019; Kaur, 2021).

In this sense, the food industry is one of the sectors that requires the highest amount of water (Keffala et al., 2017; Porwal et al., 2015; Tabelini et al., 2023). The manufacturing of dairy products is also included and is a crucial area in the food business due to its beneficial impact on human development from birth (Samkutty & Gough, 2002; Stasinakis et al., 2022). Dairy products include, for instance, milk (low-fat, full-fat, lactose-free, etc.), different varieties of cheese, butter, powdered milk, different types of yogurts including low-fat (skyr, Greek-style), full-fat, vegan, and more (Finnegan et al., 2018; Ganta et al., 2022). The manufacturing of these products is intimately linked to the generation of dairy wastewater (DWW) and solid waste, including sludge and other residues of processing.

To date, the demand for dairy products is rising due to the expanding global population. For this reason, the generation of DWW is expected to grow, leading to concerns about potential contamination of water and soil. These dangers pose a threat to human health and ecological systems (Janczukowicz et al., 2008; Kurzbaum & Bar Shalom, 2016).

Globally, between 4 to 11 million tons of dairy waste are released into water bodies, posing a significant environmental hazard (Rosa et al., 2009). DWW consists of dissolved and undissolved organic compounds, including lactose, lipids, nitrogen and phosphorus-containing chemicals, as well as chlorides (Faria et al., 2017). The presence of high organic content can reduce dissolved oxygen concentrations adversely affecting the biological processes in subsequent treatment facilities (Shete & Shinkar, 2013). At the same time, fats and oils (FAO) pose a threat to aquatic biodiversity by preventing the infiltration of oxygen from the environment into the water (Chandra et al., 2018).

Pre-treatment methods in case of DWW from yogurt production include sedimentation, flow equalization, and filtering. Then, dairy effluent can be treated using both physico-chemical and biological techniques. It has been observed that chemical procedures such as coagulation and flocculation exhibit significant efficacy in removing pollutants (Kaur, 2021; Trigueros et al., 2023). However, biological approaches are favored over physicochemical ones due to the high cost of chemical reagents (Kumar et al., 2021). For this reason, biological treatment using activated sludge becomes the dominant method for DWW treatment (Anlı & Şanlı, 2019; Kertész et al., 2023; Mekuria, 2022).

In this study, using the data collected during the field monitoring process, an evaluation was carried out to identify the primary hazards related to the management of DWW and the operation of the wastewater treatment plant (WWTP). Failure Mode and Effects Analysis (FMEA) is a commonly employed and is supported by international standards as a risk assessment technique (Adar et al., 2017; Gopal & Panchal, 2021; Wessiani & Sarwoko, 2015; Xu et al., 2022). Using this methodology, water utilities and private stakeholders can implement a structured process to identify potential failures, determine their root causes, and reduce their impacts. This practice can lead to significant cost savings for companies while also reducing the risk and costs associated with an underperforming process or product (Nativio et al., 2022).

The main novelty aspect of this work is the integration of FMEA with full-scale WWTP monitoring and post-intervention verification in order to identify the risks and quantify the impact of the upgrade on the DWW quality. In this case study, a risk management approach was adopted and the work was divided into three phases: (i) monitoring the effectiveness of a WWTP treating mainly DWW from yogurt production, (ii) conducting a FMEA to minimize the risks in the production cycle and in WWTP operation, and (iii) after the implementation of corrective actions, monitoring DWW again to assess whether any qualitative variations were present and updating the FMEA. The results can be useful for (i) the scientific community, by providing knowledge about the risks arising from the operation of a small WWTP serving a large industrial producer, and (ii) technical operators, by offering important information on the risks associated with WWTP operation and yogurt production. Furthermore, this case study highlights the importance of integrating FMEA with WWTP monitoring and post-intervention verification, serving as an example for the management of facilities treating industrial wastewater, not limited to the dairy sector.

2 Material and Methods

2.1 Characteristics of Dairy Wastewater

Samples were taken in a WWTP serving a small village in the Czech Republic and the local dairy industry has been monitored. The plant (750 population equivalent—P.E.) treated the sewer from the urban area (around 50% of the total load) and DWW from a local factory producing yogurt (the other 50%). After the release during the production process, the DWW was pre-treated in a fat trap (volume: 9 m^3) and then flowed into the sewer system where it was mixed with urban wastewater, and then treated in a WWTP (Fig. 1). It consists of a pumping station (volume: 11 m^3), a mechanical pre-treatment (12 m^3), denitrification process (56.6 m^3), the oxidation and nitrification step (116 m^3), a settlement tank (46 m^3), and a tank for sludge storage (64 m^3).

In the preliminary monitoring, samples were taken before the fat trap (initial characteristic of DWW) (SPi), immediately after the fat trap (SP1), at the pumping station (at the entrance to the WWTP) (SP2), and after treatment (outlet of the WWTP – SP3). The monitoring has been carried out for one week with daily samplings ($n = 7$). After the FMEA highlighted some critical issues, some corrections were adopted (please, see Section 3.2 for details) and the DWW exiting the fat trap (SP1)

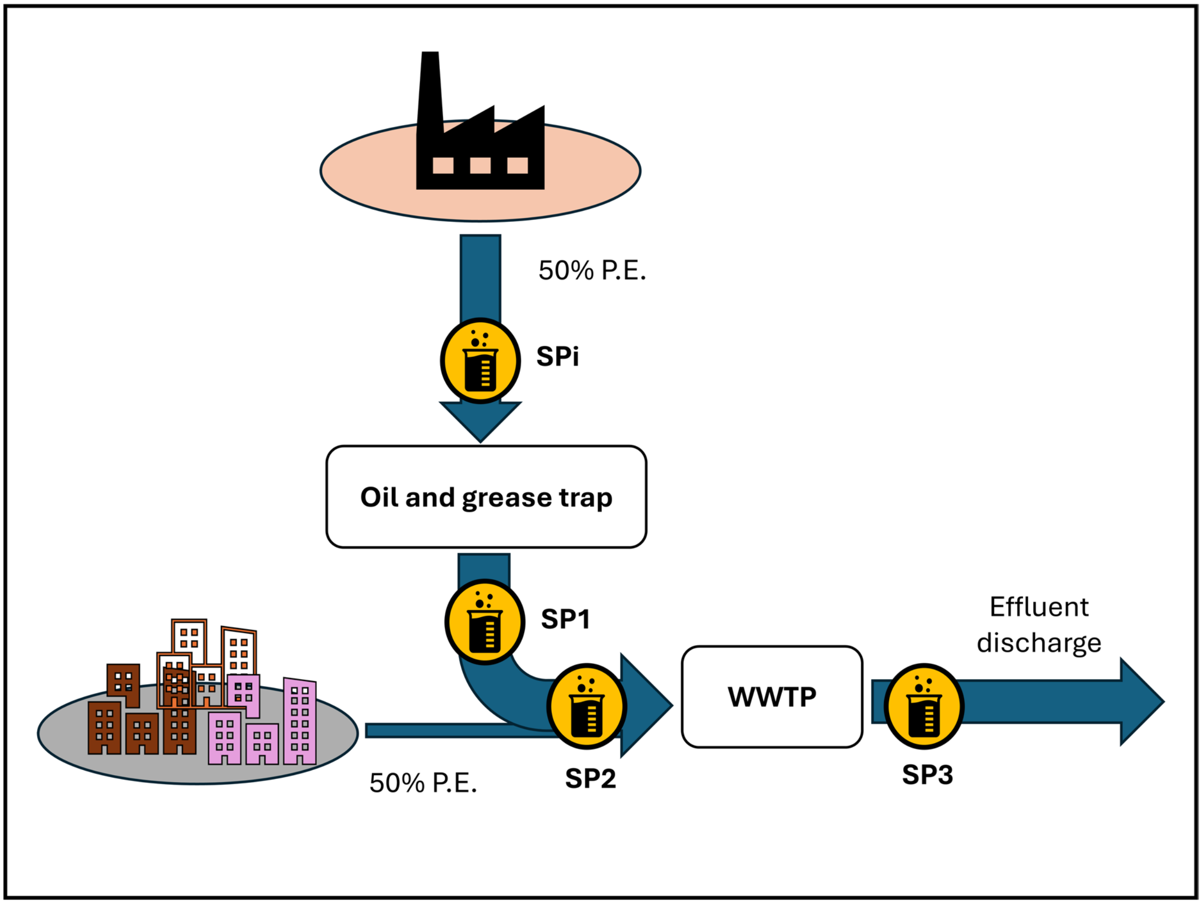


Fig. 1 Samping points (SP) considered in the study. P.E.: population equivalent

was monitored again for approximately two months (with a sampling frequency of once a week, in total n = 8).

For all sampling activities, median samples on 24 h have been taken to consider potential fluctuation of the pollutants load. The main characteristics of the DWW at SPi are reported in Table 1.

2.2 Analytical Methods

Total suspended solids (TSS) were measured according to Method 8006 (HACH, 2010). The biochemical oxygen consumption after a period of 5 days (BOD_5) represents the amount of oxygen consumed by microorganisms during biochemical processes in water and was determined using a membrane electrode to estimate the dissolved oxygen concentration. COD, $N\text{-}NH_4^+$, $N\text{-}NO_3^-$, phosphorus as orthophosphate ($P\text{-}PO_4^{3-}$) were determined using HACH kits. For spectrophotometric measures HACH DR-5000 was used. The Hach-Lange IL 550 TOC-TN device, which works on the principle of oxidation pyrolysis, was used to determine total nitrogen (N_{tot}). Organic nitrogen (N_{org}) was calculated as the difference between total nitrogen and the sum of ammoniacal and nitrate nitrogen.

Temperature and pH were measured using a portable multiparameter instrument (WTW 3410 SET4) and the probe WTW-IDS Model SenTix® 940 while conductivity was measured using the probe Model TetraCon® 925. Turbidity was quantified using the Turbidimeter HACH 2100Q.

In addition, fats and oils (FAO) were determined according to ČSN 75 7506 (Water quality—Determination of extractables by infrared spectrometry (ELIR)). The first step consisted of the sample's acidification by adding sulphuric acid. This was followed by adding sodium chloride and the extraction reagent 1,2,2-trifluoro-1,1,2-trichloroethane (TTE). The clear extract is then filtered through a cotton wool filter and then placed into the measuring cell of the spectrophotometer. The measurements were carried out at a wave number between 2400 cm^{-1} and 3400 cm^{-1}.

Table 1 Chemical and biochemical properties of the DWW at SPi compared to urban WW. u.m.: unit of measure. n.a.: not available. FAO: fats and oils. [a]: data was taken from (Henze & Comeau, 2008); [b]: expressed as total BOD

Parameter	u.m	DWW (SPi)	Urban WW [a] (as comparison)
TSS	$mg \cdot L^{-1}$	240–910	250–400
BOD_5	$mg \cdot L^{-1}$	140–670	230–350 [b]
COD	$mg \cdot L^{-1}$	665–2500	500–750
N_{tot}	$mg \cdot L^{-1}$	22.8–44	30–60
$P\text{-}PO_4^{3-}$	$mg \cdot L^{-1}$	4.49–9.16	4–10
FAO	$mg \cdot L^{-1}$	143–193	n.a
pH	-	11.1–11.4	n.a

2.3 Removal Efficiencies

For each pollutant, removal efficiencies have been calculated according to Eq. 1:

$$Removalyield(\%) = \frac{L_0 - L_i}{L_0} * 100 \tag{1}$$

where L_0 and L_i represent the load of pollutant before and after the i-th phase of the treatment system, respectively.

2.4 Failure Mode and Effects Analysis (FMEA)

Failure Mode and Effects Analysis (FMEA) is commonly used to identify potential concerns associated with industrial operations in several fields (Li et al., 2021; Zhang et al., 2024; Zhu et al., 2021). Although FMEA has several disadvantages, including the subjectivity of risk assessment (Adar et al., 2017), it was chosen over other methods (e.g., fuzzy FMEA) due to its greater ease of application. The goal is to provide the results of a combined FMEA-monitoring approach that can then be replicated quickly and easily to other case studies.

In this study, FMEA has been carried out to quantify the risks related to the production of dairy products, the release of wastewater into the sewage system and subsequent treatment. The management of the production facility and WWTP‘s operators were consulted before defining the scheme of the risk assessment. Five sequential phases were identified: three refer to the production facility, and the others to the treatment of wastewater (Fig. 2).

For each phase, based on the discussion with the different stakeholders, diverse risks were taken into consideration (Table 2). After the results of the analysis, some actions were implemented to reduce the risk

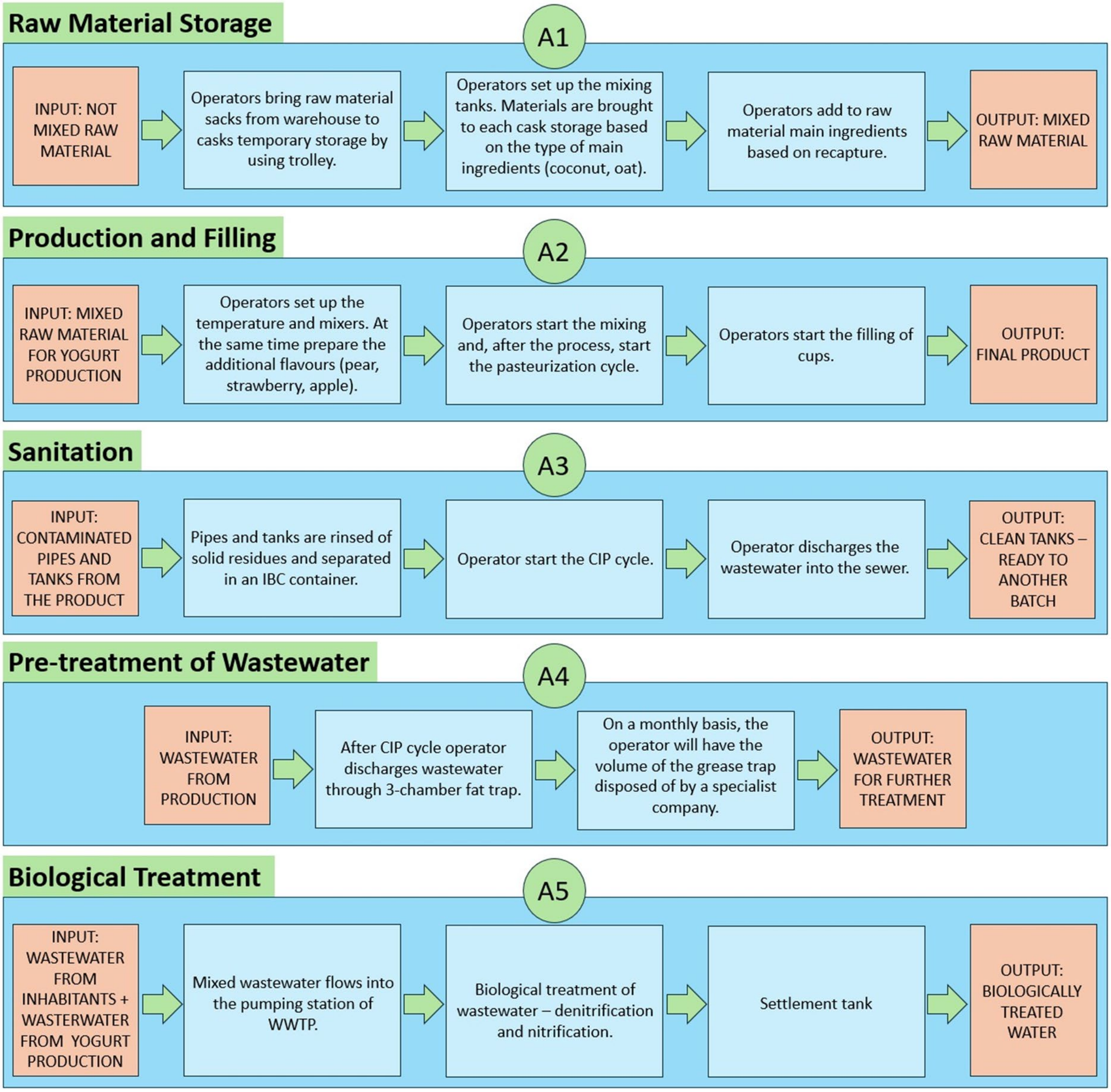


Fig. 2 Scheme of the risk assessment of the monitored case study. CIP: Clean-In-Place

(please, see Section 3.2 for details) and the FMEA was carried out again.

For each risk, the FMEA score was calculated according to Eq. 2:

$$FMEAscore = P * S * D \tag{2}$$

where P is the probability of occurrence of the event, S is the severity of the damage and D the detectability. P, S and D assume values from 1 to 10. Higher values of P and S correspond to a more certain and hazardous event, respectively, while in case of D a higher value reflects an almost impossible detectability of the event (Stamatis, 2003). A panel of experts carried out the evaluation of the risks, and each score has been assigned after discussion only when complete consensus has been reached. The panel was formed by the technical manager of the production in dairy factory, the technologist responsible for the operation of the WWTP, and one of the authors of the present manuscript specialized in FMEA. Generally,

Table 2 List of risks and consequences in each phase

	Risks	Consequences
Phase A1: Raw material storage		
R1	Operators may accidentally spill raw material from the barrel into the drainage chute during mixing	Significant contamination of the wastewater
Phase A2: Production and filling		
R2	During production, the valve drives are faulty	The operator has to dispose of some batches into the sewer, causing an increase in the pollutants load in the wastewater
R3	Agitator motors can undergo malfunctions during the production phase	Repairing the engine can take several hours and therefore the batch must be disposed of causing an increasing of pollutants load in the wastewater
R4	During product filling, the electric drive of the filling valves may be damaged	The resulting effluent flows into the sewer system. The product volume is minimal
Phase A3: Sanitation		
R5	Phase separation (between production and CIP cycle) is carried out based on operator experience instead of automated measurements (e.g., turbidity), increasing the risk of process inconsistency	Uncontrolled pollution of wastewater happens
R6	Production of wastewater after sanitation flows according to a typical Clean-In-Place (CIP) cycle without turbidity monitoring or an additional separation stage	Uncontrolled pollution of wastewater happens
Phase A4: Pre-treatment of wastewater		
R7	If the operator misses to dispose of the grease trap volume due to human error, it can reduce the effectiveness of pre-treatment	If this wastewater is not properly pre-treated, it can negatively affect the biological treatment
Phase A5: Biological treatment		
R8	The pumping station is at risk of float probe failure. This is commonly caused by a high concentration of fatty substances in the water	During the replacement of the probes, untreated wastewater can flow through the by-pass into the river without treatment
R9	The air distribution in the nitrification zone is variable and not homogeneous	The aeration system is overextended handling a higher air pressure than it was engineered for being at risk of damage
R10	Excess sludge is not regularly drained to the sludge tank	Effluent contamination with sludge due to clarifier overloading

relevant risk is assumed when the FMEA score exceeds 100 and that indicates the failure that should primarily be tackled (Adar et al., 2017).

3 Results and Discussion

3.1 Monitoring of WWTP and Production of DWW

This dairy factory generated an effluent with a diverse range of characteristics. The great variability and unpredictability of the planned Clean-In-Place (CIP) cycles led to inconsistent effluent generation. These sanitation methods result in a significant amount of DWW produced. Within the alkaline range, the pH value of the wastewater remained very stable, ranging from 11.2 to 11.5. Generally, in CIP, after alkaline phase, the final cleaning step commonly involves the use of acid (in this case HNO_3), that should complete the cleaning and neutralize the wastewater stream. However, the high pH observed in all post-CIP samples is likely due to the predominance of alkaline cleaning steps in CIP operations, probably combined with incomplete neutralization. The mixing of DWW with neutral urban sewers at the entrance of the WWTP reduced the pH value to 7.8—8.5.

The DWW generated during the manufacturing of yogurt products consists of both organic and inorganic pollutants, such as nitrogen and phosphorus in various forms, due to the inclusion of processed natural ingredients in the manufacturing process of yogurt. The parameters BOD_5, COD, TSS, FAO, N_{tot}, N-NH_4^+, N-NO_3^-, N_{org}, and P-PO_4^{3-} were monitored.

3.1.1 Organic Pollutants

The quality of the discharge from the production of yogurt can be assessed by examining the outlet in the grease trap (SP1). During the 7-day monitoring period, the BOD_5 exhibited a value of 394 ± 148.1 mg L^{-1} (± refers to the confidence interval). During the monitoring at the WWTP intake (SP2), the average value of BOD_5 reduced to 228 ± 141.3 mg L^{-1} and after biological treatment (SP3) decreased to 164 ± 103.1 mg L^{-1} (Fig. 3a).

The minimum COD value at SP1 was 665 mg L^{-1}, the median value was 1990 mg L^{-1}, and the maximum value was 2500 mg L^{-1}. At SP2, the median COD value was measured as 1020 mg L^{-1}, with the highest recorded value being 1790 mg L^{-1}. After biological treatment (SP3), the lowest COD was 109 mg

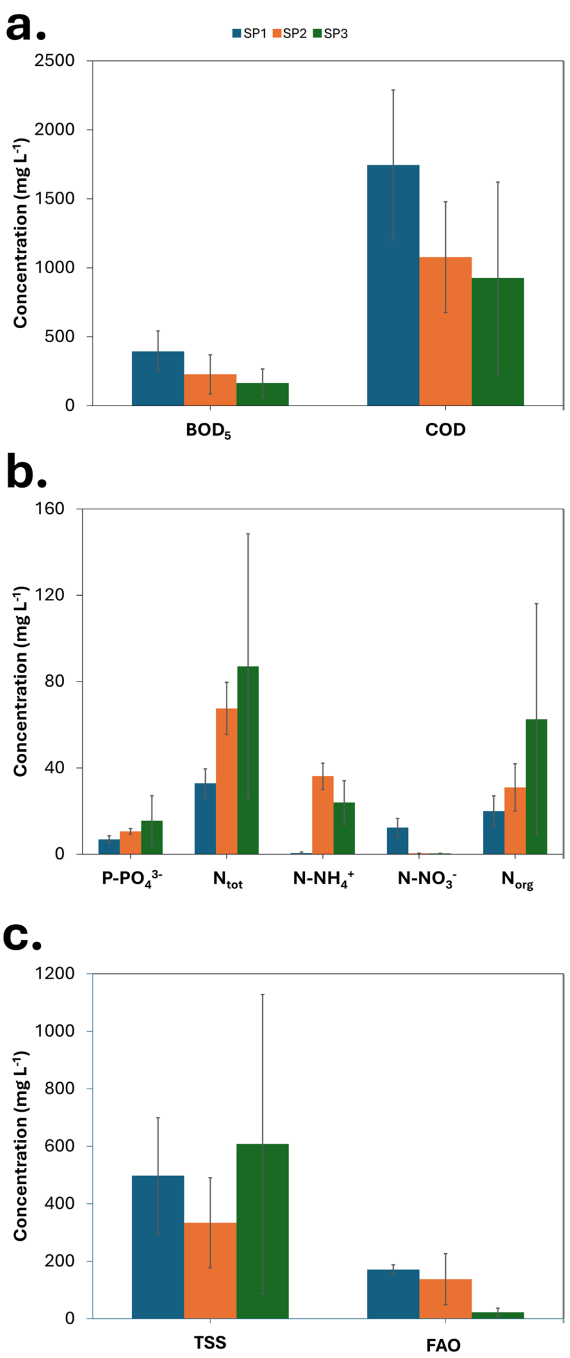


Fig. 3 Concentration of **a** BOD_5 and COD, **b** P-PO_4^{3-}, N_{tot}, N-NH_4^+, N-NO_3.$^-$ and N_{org}, **c** TSS and FAO in sampling points SP1, SP2, and SP3. The bars represent the 95% confidence intervals (n = 7)

L^{-1}, the median value was 660 mg L^{-1}, and the maximum value recorded was 2230 mg L^{-1}.

In previous studies, BOD_5 and COD content of the raw wastewater produced during dairy product manufacturing in Brazil was measured as 723 mg L^{-1} and 2320 mg L^{-1}, respectively (Alves Rabelo et al., 2017), similar to those found in the present work. In another study, the BOD_5 concentration in DWW ranged from 1300 to 1500 mg L^{-1}, and COD concentration ranged from 2000 to 10,000 mg L^{-1} (Koyuncu et al., 2000), higher than those monitored in this plant probably due to different dairy products.

3.1.2 Nitrogen and Phosphorus

In SP1, the $N\text{-}NH_4^+$ concentration ranged from 0.05 mg L^{-1} to 1.63 mg L^{-1}. The median value of $N\text{-}NH_4^+$ in SP2 was measured as 37.90 mg L^{-1} with a minimum of 28.20 mg L^{-1} and a maximum of 46.20 mg L^{-1}. The median $N\text{-}NH_4^+$ concentration in the effluent of the WWTP (SP3) was 31.20 mg L^{-1} (Fig. 3b). During the monitoring, after the grease trap (SP1) $N\text{-}NO_3^-$ was in the range of 6.91—20.10 mg L^{-1}. After the mixing with urban wastewater (SP2), $N\text{-}NO_3^-$ concentration was 0.4 mg L^{-1}, the same as after the process of biological purification (SP3).

In SP1, a minimum N_{tot} concentration of 22.80 mg L^{-1} was detected with a median value of 30.60 mg L^{-1}. N_{tot} in SP2 was in the range of 46.6—88.30 mg L^{-1}, with a median value of 70.30 mg L^{-1}. This value was lower in SP3 after biological treatment (58.80 mg L^{-1}).

In SP1, $P\text{-}PO_4^{3-}$ in DWW was in the range of 4.49—9.16 mg L^{-1}, with a median value of 6.22 mg L^{-1}. In SP2, the concentration of orthophosphate increased probably due to the higher load in urban sewer reaching 7.76—12.10 mg L^{-1} (median: 11.30 mg L^{-1}). After biological treatment, $P\text{-}PO_4^{3-}$ was detected in the range of 1.03—31.60 mg L^{-1}.

The concentration of nitrogen and phosphorus in SP1 are coherent with previous literature results. (Demirel et al., 2005) found that N_{tot} in DWW was 14–272 mg L^{-1} and P_{tot} (data on $P\text{-}PO_4^{3-}$ are not available) was 8–68 mg L^{-1}, similar to those found in the present study. Additionally, a different study highlighted that the $N\text{-}NH_4^+$ parameter varies between 1 and 184 mg L^{-1} (Finnegan et al., 2018). According to another work, the N_{tot} concentration in DWW ranged from 39 to 141 mg L^{-1}, while the P_{tot} (data on $P\text{-}PO_4^{3-}$ are not available) ranged from 20 to 104 mg L^{-1} (Arunadevi & Saravanaraja, 2020).

3.1.3 Suspended Solids and FAO

TSS in DWW was detected in the range of 240—910 mg L^{-1}, with a median value of 390 mg L^{-1} (Fig. 3c). In SP2, the median value was lower (287 mg L^{-1}) but higher concentration were detected in SP3 with value up to 1490 mg L^{-1}. In previous works, the TSS parameter in DWW was measured in the range of 205 to 2370 mg L^{-1} (Finnegan et al., 2018) in line with the results of the present study.

The concentration of FAO after the grease trap was 143—193 mg L^{-1}, with a median concentration of 172 mg L^{-1}. In SP2, the median FAO concentration was lower (110 mg L^{-1}) due to the mixing with urban sewer. After the WWTP, the concentration of FAO decreased up to 15.10 mg L^{-1}. The results are in line with previous studies which highlighted a concentration of FAO in DWW equals to 30 mg L^{-1} (Alalam et al., 2021). In another study, the quality of DWW was monitored and the concentration of FAO was measured as 74.2—14,515 mg L^{-1} (Tabelini et al., 2023).

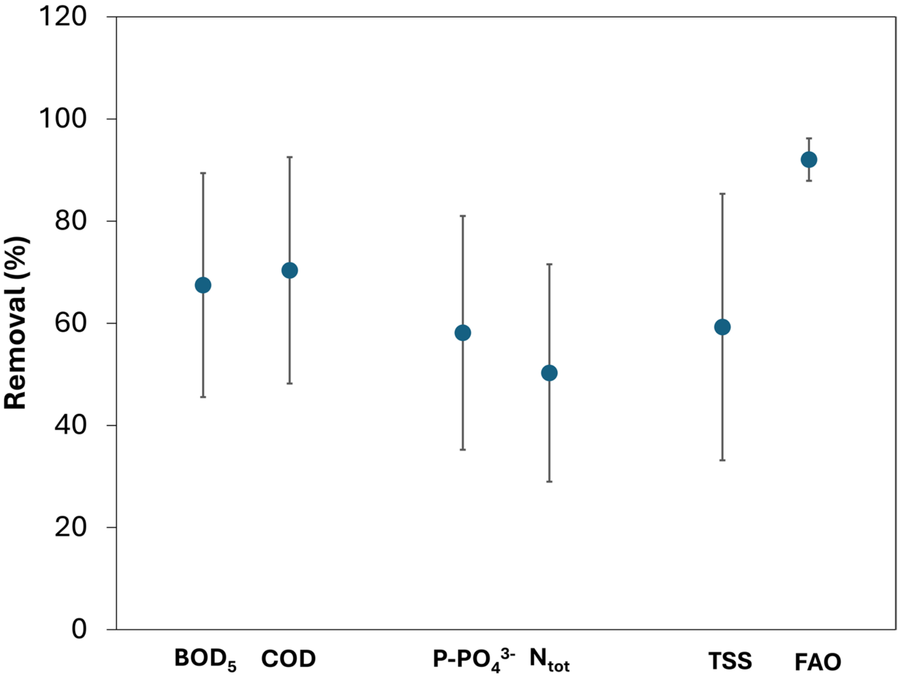
3.1.4 Removal Efficiencies of the WWTP

The effectiveness of the WWTP on the removal of organic substance, orthophosphate, nitrogen, solids and FAO was calculated. The removal of organic substance remain lower than expected with 67.5 ± 21.9% of degradation of BOD_5 and 70.4 ± 22.1% of degradation of COD (Fig. 4).

Total nitrogen and ortophospate removal reached 50.3 ± 21.3% and 58.1 ± 22.9%, respectively, indicating the non-optimal performance of the biological process. TSS were removed up to 59.3 ± 26.1% while good performance in line with conventional WWTP were recorded for FAO (92 ± 4.2%).

Despite the good performance of the WWTP against FAO, this pollutant could have a role in reducing the performance of the treatment facility against other pollutants. Still-high FAO concentration could limit the efficiency of aeration units, reducing the dissolved oxygen in the aerobic reactors (Dehghani et al., 2014). This aspect seems to be confirmed by the measures of dissolved oxygen in the aerobic reactor which remains at around 1 mg L^{-1} during the 7 days

Fig. 4 Removal efficiencies of BOD_5, COD, $P\text{-}PO_4{}^{3-}$, N_{tot}, TSS and FAO in the WWTP. The bars represent the 95% confidence interval (n = 7)



of monitoring (Figure S1). This interpretation, however, should be treated with caution. The low oxygen concentration in the reactor could be due to an undersizing of the aeration system and the poor removal of other polluting parameters could be accentuated by an inhibitory effect on the biomass of other substances present in the wastewater. For these reasons, evaluation of microbial activity, such as oxygen uptake rate (OUR) analysis (Collivignarelli et al., 2021) and tests on the efficiency of the oxygen transfer in the reactor are suggested in future studies.

Moreover, the monitoring revealed that DWW showed a high level of resistance to biological degradation, making it harder for biological wastewater treatment to treat it. In fact, the BOD_5 COD^{-1} ratio at the entrance to the WWTP (SP2), which contains a mixture of DWW and urban wastewater, varied between 0.08 and 0.23. This range is highly atypical for biological processes, as the recommended BOD_5 COD^{-1} ratio (which indicates the substrate's biological degradability) should be around 0.4 (Lacalamita et al., 2024). Also, due to the limited performance, during the monitoring, the biological WWTP under investigation failed to meet the required effluent parameters for organic and inorganic pollutants (Czech Government 2016).

3.2 FMEA Risk Assessment of DWW and WWTP

The experience of the stakeholders guided the selection of risk locations, targeting areas with a higher probability of experiencing issues related to the release of concentrated effluent from sanitation or operational concerns. Ten risk locations have been located and classified as R1-R10. These concerns are related to the specified scheme of dairy product manufacturing, which includes the treatment of wastewater (Table 2).

The risk analysis revealed that five out of the ten evaluated risk situations achieved a score exceeding 100 (Table 3).

According to the results, the production of DWW after sanitization, according to a typical Clean-In-Place (CIP) cycle, presents the highest FMEA score (180) due to the discharge of DWW containing high levels of FAO without turbidity monitoring or an additional separation stage. Moreover, during the production process, operators may accidentally discharge products significantly contaminated with organic compounds and fats leading to operational difficulties at the WWTP. Among the main difficulties is the malfunction of the pumping station, due to incorrect level detection and manual control of the pump.

Table 3 Results of the FMEA. The relevant risks (score > 100) are reported in bold. Green indicate lower value of the parameters, yellow is medium–low, orange refers to medium–high and red symbolyze high value. P: probability of occurrence; S: severity of the damage; D: detectability of the event. For the description of each single risk, please refer to Table 2

Risk	P	S	D	FMEA score
R1	3	4	5	60
R2	7	3	7	**147**
R3	3	5	2	30
R4	3	4	2	24
R5	8	7	2	**112**
R6	10	6	3	**180**
R7	4	3	7	84
R8	8	6	3	**144**
R9	3	3	7	63
R10	7	6	3	**126**

3.3 Upgrade of the System

Given the results of the FMEA and the results of the monitoring of the WWTP, several corrections were implemented to reduce the four major risks of failure (R2, R5, R6, R10). The proposal to install an ultrasonic probe has not been already implemented, consequently the risk related to the pumping station (R8) remains.

About R2, three new electrovalves with remote failure notification were installed at a point on the pipeline route where failures were most frequent. The new valves have a tighter seal compared to the old ones, which helps avoid any leakage into the sewer system. Subsequently, the operator divides all the products into barrels and arranges their disposal. After three months, this issue was significantly reduced. The operator identified only five fault conditions and only released a small quantity of wastewater into the sewer. For this reason, the updated FMEA score was reduced to 16 (Table 4).

R5 and R6 were limited thanks to the installation of two turbidimeters on the outlet pipe to detect highly turbid water and send it into the newly constructed separation tank for highly contaminated water. The water flows into the grease trap only when the turbidity is low. After two months, the approach proved to be effective.

The risk that the effluent is contaminated with sludge (R10) was reduced increasing the frequency of excess sludge removal, resulting also in better quality of the activated sludge. Turbidity has been detected in the treated water only during storm events.

The corrections implemented to limit the amount of FAO entering the WWTP (i.e. turbidimeter and flush separation of oils) were effective to act against what has been considered the possible main reason for the low performance of the WWTP against organic substances. After the implementations, the

Table 4 Results of the updated FMEA on R2, R5, R6 and R10. Green indicate lower value of the parameters, yellow is medium–low, orange refers to medium–high and red symbolyze high value. P: probability of occurrence; S: severity of the damage; D: detectability of the event. For the description of each single risk, please refer to Table 2

Risk	P	S	D	FMEA score
R2	1	2	8	16
R5	3	2	2	12
R6	3	2	2	12
R10	3	2	2	12

DWW exiting the fat trap (SP1) has been monitored and TSS, COD and FAO were reduced on average by 72.4%, 50.9% and 39.5%, respectively, compared to the previous scenario (Fig. 5). In particular, the concentration of FAO was reduced below 100 mg L^{-1}, closer to the same values as in urban wastewater (Quéméneur & Marty, 1994).

4 Conclusions

This study demonstrates how the integration of FMEA with large-scale monitoring can support proactive risk management in WWTPs treating DWW. The results of the monitoring highlighted that the functioning of the WWTP could be impacted by the low biodegradability of the wastewater and by the high concentration of FAO that could have limited the diffusion of oxygen in the biological reactor. However, this last aspect remains speculative and warrants further investigation to exclude undersizing of the aeration system and the inhibitory effect of other pollutants on the biomass. The FMEA revealed that five out of the ten evaluated situations achieved a score of relevant risk. The primary issue is the discharge of DWW containing high levels of FAO after sanitization in CIP cycle without turbidity monitoring or an additional separation stage. Moreover, operators could accidentally discharge in sewer products significantly contaminated with organic compounds and fats also during the production process, leading to operational difficulties at the WWTP. The actions implemented to limit the amount of FAO entering the WWTP (i.e. turbidimeter and flush separation of oils) proved to be effective and significantly reduced the score in the FMEA. TSS, COD and FAO in the DWW (SP1) were reduced by 72.4%, 50.9% and 39.5%, respectively, compared to the previous scenario. The concentration of FAO was reduced below 100 mg L^{-1}, closer to the same order of magnitude as in urban wastewater.

The case study presents some limitations, such as a short monitoring period (one week and two months before and after the upgrade, respectively) and analysis limited to a single WWTP. However, the results are useful because this combined FMEA-monitoring approach could be potentially applied to other industrial WWTPs, even of different capacities, to enhance process stability, and improve the resilience of biological treatment systems. Beyond the specific case study, several operational lessons can be drawn such as the need of controlling industrial WW at the source and the importance of preventive actions at critical control points (e.g., real-time turbidity monitoring and the separation of oil-rich flushing streams) to improve the WW quality instead of

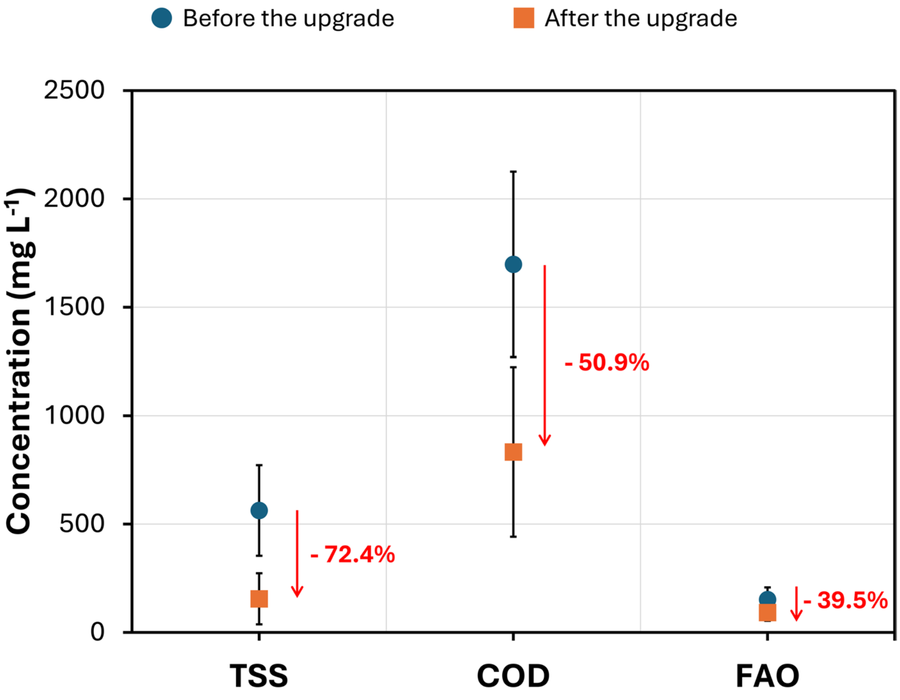


Fig. 5 Concentration of TSS, COD and FAO in sampling point SP2 before (n = 7) and after (n = 8) the upgrading and average decrease in concentration. The bars represent the 95% confidence interval

downstream corrective measures. In future, the combined FMEA—monitoring approach could be applied to other WWTPs, adapting the list of risks considered and pollutants monitored to the specific needs of the case study. Additionally, the application could then be extended to urban WW case-studies, including risk assessments and water quality monitoring from the sewer system to the treated effluent discharge.

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Declarations

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