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Determinants of water consumption in the dairy industry

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This paper analyzes the correlations between selected technical, process and production factors, equipment profiles and water consumption statistics in four types of dairy plants. Dairy plants were surveyed both individually and in groups. Water consumption was most highly correlated ($r > 0.868$) with equipment profiles. The highest water consumption was observed in dairy plants operating milk powder departments. In those plants, organization and production factors could significantly reduce water consumption levels because in addition to milk powder, those plants also supplied eight other products. The indicators of water consumption per unit of the final product were correlated (at $0.820 > | r | > 0.663$) with equipment profiles, the degree of process automation and employment. Variations in water consumption per unit of the final product were best explained in small plants supplying several products. The presented equations can be used to optimize water demand of various types of equipment and to determine the correlations with energy consumption for wastewater treatment. Our results can contribute to the development of water consumption models in dairy plants and the implementation of clean production standards.

Keywords: dairy industry, water consumption, environment.

INTRODUCTION

Polish industrial plants consumed 651.6 hm^3 of water in 2011. Twenty branches of the food processing industry had a combined 10.53% share of the above consumption. The pollutant loads of wastewater evacuated from food processing plants are determined by the chemical composition of processed materials, the applied production technologies and seasonally high quantities of waste with varied water content[1–7]. Milk processing is a branch of the food industry. Milk and dairy markets are among the largest segments of the food market. In 2011, cow milk purchases reached 9043 million liters, and they accounted for 75.0% of the national milk output. Dairy plants are intensive users of energy carriers, including water. In the food industry, 33.96% of water was consumed by dairy producers. Around 97% of water in dairy plants was drawn from own wells[8]. In dairy plants, water consumption levels are determined by production output and the applied technologies. The implementation of adequate production hygiene standards, the need to reduce water consumption and increase the effectiveness of wastewater treatment in various branches of the food processing industry have been discussed by numerous authors[9–16].

The microbiological quality of milk determines the range of heat treatments in a dairy plant, and it affects the usage of cooling water in heat exchangers and the consumption of cleaning water. The effects of milk production and processing on the environment and the ecological footprint of dairy plants have been discussed by Berlin et al.[17], Drastig et al.[18], Flemmer[19], Honkasalo et al.[20], Masse et al.[21], Merete[22], Milani et al.[23], Prasad et al.[24], Sonesson and Berlin[25], Steinhoff-Wrześniewska et al.[26], Svensson et al.[27], Wojdalski and Dróżdż[28].

The effects of production processes and operations on the quantity and composition of dairy effluents have been analyzed by Baras and Jovanovič[29], Baskaran et al.[30], Briao et al.[31], Demirel et al.[32], Mulligan et al.[33], Perle et al.[13], Talik and Kutera[34]. Effluent volumes are related to water consumption. Kowalczyk and Karp[35] investigated the energy efficiency of wastewater treatment in the dairy industry.

The existing body of literature on rational water use in the dairy industry does not fully explain the significant variations in dairy plants' water demand. According to published research results, most dairy plants consume from 1 to 10 m^3 of water per every m^3 of processed milk (Table 1). The referenced studies investigated the water consumption profile in different production departments as well as dairy plants' total water demand. In plants producing a variety of dairy products, the indicators of water consumption per unit of final product cannot be accurately determined. According to the Energy Performance Indicator Report[36], the energy consumption of the Cleaning-In-Place method deployed by Canadian dairies reaches 0.0001–0.0930 kWh/L of milk.

The indicators of water consumption per unit of the final product given in reference documents, including Bosworth et al.[38] and WS Atkins Polska[39], were calculated based on the results of the measurements performed in a limited number of production plants. Other publications[44] quote indicators of water consumption per unit of the final product without accounting for the specific parameters of the surveyed dairy plant. Some authors, among them Budny et al.[45–47], Steffen et al.[48], Wojdalski et al.[49], Wojdalski and Dróżdż[50, 51] and EPIR[36], made attempts to determine the correlations between selected processing technologies, equipment profiles and water

Table 1. Benchmarking of water consumption and wastewater disposal from dairy plants

Type of plant		Indicators of water use and wastewater management		Source
Number of plants (location)	Production profile	Range of values	Unit	
7 (Australia)	White and flavored only	1.05–2.21	L water / L processed milk	Prasad et al.[24]
3 (Australia)	Cheese and whey products	0.64–2.90		
10 (Australia)	Powdered products	0.07–2.70		
Dairy plants in Canada		1.0–5.0	L water / L processed milk	Wardrop Eng. Inc.[37]
Dairy plants in Poland (total)		7.0	L water / L processed milk	WS Atkins Int.[7]
Dairy plants in Denmark (total)		2.21–9.44	L water / kg product	Bosworth et al.[38]
8 (Sweden)	Milk and dairy drinks	0.98–2.80	L water / L processed milk	WS Atkins Polska[39]
3 (Denmark)		0.60–0.97		
8 (Finland)		1.20–2.90		
1 (Norway)		4.10		
1 (Poland)		0.5–0.75		
4 (Sweden)	Cheese and whey products	2.0–2.5	L water / L processed milk	
5 (Denmark)		1.2–1.7		
2 (Finland)		2.0–3.1		
2 (Norway)		2.5–3.8		
1 (Poland)		2.22		
7 (Sweden)	Milk powder, cheese and/or dairy drinks	1.7–4.0	L water / L processed milk	
3 (Denmark)		0.69–1.90		
2 (Finland)		1.40–4.60		
2 (Norway)		4.60–6.30		
5 (Poland)		1.80–5.30		
1 (USA)	Fluid products	1.89	Water use/product kg/kg)	Carawan et al.[40]
	By-products	10.5		
	Frozen products	15.7		
	Total products	3.57		
Dairy plants in Poland (total)		3.48–9.77 Average of 6.08	L water / L processed milk	Wojdalski et al.[41]
1 (Lithuania) Company data	Cream	3.28	L water / kg product	Dvarionienė et al.[42]
	Butter	3.99		
	Canned products	7.438		
	UHT	2.7		
11 (France)	N/A	0.2–10.0	L wastewater / L processed milk	Vourch et al.[43]

consumption in dairy plants. The analyzed problem requires an appropriate research methodology, including model solutions that emphasize the systemic character of water consumption analyses[52, 53].

Taking into account the existing level of knowledge in the reviewed literature, the objective of this paper was to analyze the correlations between three types of factors, namely technical factors (including the degree of process automation), production factors and equipment profiles, and water consumption statistics in four types of dairy plants. This study also aims to supplement databases used in the development of water consumption models in dairy plants. The results will be used to formulate recommendations for industrial practice, with regard to environmental aspects of water management which could reduce water consumption and contribute to an improvement in hygiene standards in the dairy industry. The aim of the study is correlated with the objectives formulated by Bunse et al.[54] who pointed to the gap between the research needs reported by manufacturing plants and the available scientific publications.

MATERIALS AND METHODS

In this study, we analyzed the results of surveys performed in 139 dairy plants in summer and in 81 dairy plants in winter. Dairy plants were selected randomly in view of their daily processing output, production profile and equipment, with special emphasis on the installed capacity of electrical devices. Similarly to the study described by WS Atkins Int.[7], water consumption was determined based on audit measurements and questionnaires returned by production plants. The analyzed

Table 2. Types of surveyed dairy plants

Type of dairy plant	Processing profile
T1	Processed milk, dairy drinks, cream, cottage cheese, hard cheese, butter, casein, milk powder
T2	Identical to T1 but without milk powder
T3	Identical to T1 but without processed milk, dairy drinks, cream and cottage cheese
T4	Only processed milk, dairy drinks, cream and cottage cheese

Table 3. Factors affecting water consumption in dairy production

Group of factors	Description	Symbols*
FR1	Basic parameters characterizing dairy plants and indicators of plant automation	AP, ME_1, ME_2, ML, N_1, N_2, P, PE_1, PE_2, S, V_1, V_2, Z, Z_m
FR2	Production profile	Z_1, Z_2, Z_3, Z_4, Z_5, Z_6, Z_7, Z_8, Z_9, Z_{10}, Z_{11}
FR3	Equipment profile	P_1, P_2, P_3, P_4, P_5, P_6, P_7, P_8

*– the applied symbols are explained in the "Symbols and abbreviations" section.

plants were divided into four groups based on their milk processing profiles, as demonstrated in Table 2.

Each plant listed in Table 2 was characterized using the three groups of factors described in Table 3. To ensure that our results can be processed into practical applications for the dairy industry, the survey analyzed water consumption per unit of final product (*WU*), a factor defined by Budny et al.[46, 47], Wojdalski et al.[49], Neryng et al.[55] and Wojdalski and Dróżdż[56]. A similar methodology was adopted to examine the correlations between various factors and water consumption and fruit and vegetable processing plants[57].

The tested hypothesis was that the factors listed in Table 3 (*FR1, FR2* and *FR3*) are correlated with water consumption (*WD* and *WU*). Similar factors were adopted by other authors, including Budny et al.[47] and Wojdalski and Dróżdż[50], to evaluate their impact on water use in dairy plants. Group *FR1* includes 13 factors which characterize the analyzed plants and selected technical solutions. Previous research justified the combined use of a plant's total installed capacity (*P*) and daily processing output (*Z*) to evaluate the dairy plant's water consumption. The above approach was applied in this study, and the respective methodology was modified for the needs of our research. In view of their significance for industrial applications, the factors for mathematical descriptions were selected with the aim of addressing the complexity of the investigated problem. To a certain extent, this study accounts for a cause-effect relationships in water usage. The adopted factors (independent variables) illustrate the concept adopted at the project design stage. Development density and the length of internal service roads on industrial premises were not taken into account, and the total area of the dairy plant (*S*) was expressed as an independent variable and in relation to the plant's processing output (*AP*). The cubic capacity of production facilities (V_1) and the total cubic capacity of a dairy plant (V_2), including auxiliary departments and the administration building, were regarded as independent variables. They are related to the size of technical equipment, cable length, processing line solutions and water consumption *(WD)* for cleaning and sanitizing operations. The degree of plant automation and equipment use relative to employment in production departments and organizational standards were expressed with the use of indicators ME_1, ME_2 and *ML*. Daily milk processing output per employee is illustrated by indicators PE_1 and PE_2. The above indicators constitute a basis for evaluating a plant's equipment standards and organizational effectiveness. Group *FR2* includes 11 factors that describe milk processing and production profiles in the entire dairy sector. The types of dairy plants listed in Table 2 are characterized by different processing profiles. Group *FR3* includes factors that describe the installed capacity of electrical devices which is related to equipment profiles. Statistical analyses were carried out to determine the coefficient of correlation *r* between *FR1, FR2* and *FR3* factors and independent variables *WD* and *WU*. Coefficient *r* can also be used to determine the analyzed factors' influence (described as coefficient of determination R^2) on water consumption *WD* and water consumption per unit of final product *WU*.

Stepwise regression equations were developed in the statistical analysis process. A multiple regression model was used due to a high number of factors of varied significance. The following general formula was applied to describe water consumption (*WD* or *WU*) in the analyzed groups of dairy plants in view of various factors:

$$Y = b_0 + b_1x_1 + b_2x_2 + ...+b_kx_k$$

where: Y – dependent variable (*WD* or *WU*), x – factors forming groups *FR1*, *FR2* and *FR3*, listed in Table 3 (e.g. ME_1, ML, P, PE_1, Z_n)

The values of parameter b_i were determined for the resulting equations. The selected equations satisfied all of the below conditions:

– correlation coefficients *r* and coefficients of determination R^2 reached the highest values (r>0.6 and R^2>0.4),

– the number of independent variables did not exceed 4, and the equation did not have a complex form with the involvement of FR1 group factors described in Table 3,

– co-occurrence of factors which were not bound by a causal relationship,

– value of the Fisher-Snedecor distribution: $F_{comp} > F_{table}$ at $\alpha = 0.05$;

– value of the Student's t distribution for every factor in groups *FR1*, *FR2* and *FR3*: $t_{comp} > t_{tabl}$ at $\alpha = 0.05$.

The use of the resulting equations when the following conditions were satisfied:

$$b_1x_1 + b_2x_2 + ... + b_kx_k \geq b_0$$

$$x_i \geq 0 \text{ for } i = 1......k$$

partially explained water usage in the analyzed types of dairy plants (*T1, T2, T3, T4*). Coefficients of regression b_i also support statistical inference. The conditions when in one equation all factors $x_i = 0$ were ruled out. The results were processed statistically to produce linear regression equations (Tables 4–8) expressing variability in water consumption. Calculations were performed using STATISTICA Data Miner + QC Polish v. 9.1 software. Selected verified formulas presented by Wojdalski and Dróżdż[50, 51] are also shown.

Results

The correlations between group factors and water consumption in four types of dairy plants are presented in Tables 4–7. Dairy plants were surveyed in two seasons of the year (summer – SM, winter – W). The values of *WD* and *WU* are shown in the order of the factors shown in Table 3. The values of *WU* reported in individual plants which are not listed in Tables 4 or 7 are shown in Table 8. In this case, correlations were analyzed based on a single

Table 4. *T1* dairy plants

Total installed capacity in the analyzed group of plants *P* [kW] (No. of plants in group)	Mean daily water consumption in the analyzed group of plants *WD* [m^3]	Mean water consumption per unit of final product *WU* [m^3/1000 L]	Season	Multiple regression equation	Correlation coefficient r	Independent variables, range of variation
454.0–2421.7 (21)	948	5.50	SM	$WD = 823.82 + 3.71Z – 407.47PE_1$	0.642	Z 70–647 PE_1 0.586–3.109
318.0–2548.0 (19)	830	7.57	W	$WD=409.76+3.25Z$	0.758	Z 29–539
				$WD= 536.95 + 6.21 Z_4$	0.839	Z_4 10.4–282.7
				$WD = 227.41 + 1.60P_1 + 1.24P_4-3.78P_7 + 2.26P_8$	0.868	P_1 124.6–872.8 P_4 100.0–964.0 P_7 17.8–298.8 P_8 0.0–358.3

Table 5. *T2* dairy plants

Total installed capacity in the analyzed group of plants *P* [kW] (No. of plants in group)	Mean daily water consumption in the analyzed group of plants *WD* [m^3]	Mean water consumption per unit of final product *WU* [m^3/1000 L]	Season	Multiple regression equation	Correlation coefficient r	Independent variables, range of variation
83.0–2935.0 (37)	468	5.29	SM	$WD = -43.82 + 0.008V_2 + 0.171P + 2.622Z$	0.877	V_2 1330–141299 P 83–2935 Z 6.6–472.2
				$WD = 44.97 + 9.71Z_1 + 4.95Z_3 + 6.08Z_5 + 8.80Z_6$	0.820	Z_1 0.0–211.0 Z_3 0.0–164.0 Z_5 0.0–141.0 Z_6 0.0–157.5
				$WD = –53.86 + 1.71P_1 + 1.53P_2 + 0.86P_3 + 3.05P_7$	0.874	P_1 24.4–1155.1 P_2 140,0–652.0 P_3 250.0–956.0 P_7 20.0–157.0
30.3–1938.0 (24)	332	6.70	W	$WD = 30.641 + 0.071V_1 + 4.544Z$	0.885	V_1 358–54181 Z 6.2–186.5
				$WD= –1.35 + 0.76P_1 + 1.08P_4 + 6.42P_6$	0.867	P_1 124.6–872.8 P_4 0.0–964.0 P_6 0.0–68.0

Table 6. *T3* dairy plants

Total installed capacity in the analyzed group of plants *P* [kW] (No. of plants in group)	Mean daily water consumption in the analyzed group of plants *WD* [m^3]	Mean water consumption per unit of final product *WU* [m^3/1000 L]	Season	Multiple regression equation	Correlatio n coefficient r	Independent variables, range of variation
83.0–1923.0 (22)	298	4.18	SM	$WD = 108.57 + 2.22Z_4 + 45.93Z_7$	0.900	Z_4 10.0–335.8 Z_7 0.0– 22.5
				$WD = –113.51 + 1.19P_1 + 0.58P_2 + 2.84P_5 + 13.68P_8$	0.978	P_1 30.3–574.0 P_2 31.0–777.0 P_5 0.0–58.6 P_8 0.0–101.0
30.3–1938.0 (20)	375	5.91	W	$WD = 123.85 + 0.019V_2 – 0.3453(AP)$	0.945	V_2 1617–76435 AP 89.3–1989.1
				$WU = 10.768 – 0.472ME_1$	–0.663	ME_1 1.17–17.74
				$WD = 229.27 + 8.79Z_4$	0.877	Z_4 12.0–156.0
				$WD = 25.44 + 1.45P_2 + 6.18P_6 + 11.90P_7 + 10.52P_8$	0.970	P_2 10.5–777.0 P_6 0.0–87.0 P_7 0.0–146.0 P_8 0.0–376.8

variable – daily or monthly milk processing output (Z and Z_m) or production profile (*FR2*). In line with the applied methodology, equations which demonstrated strong correlations between *FR* group factors and water consumption were also presented. Equations representing weaker but statistically significant correlations, where the relevant factors were rarely mentioned in literature, were also listed. Regression coefficients in the presented equations support the determination of changes in water consumption *WU* or *WD* when the value of the analyzed factor is modified by one unit, while the remaining factors (independent variables) remain constant. Each factor from groups *FR1*, *FR2* and *FR3* could be subjected to independent analyses that account for both production technology and operating parameters. Examples of their

Table 7. *T4* dairy plants

Total installed capacity in the analyzed group of plants *P* [kW] (No. of plants in group)	Mean daily water consumption in the analyzed group of plants *WD* [m^3]	Mean water consumption per unit of final product *WU* [m^3/1000 L]	Season	Multiple regression equation	Correlation coefficient r	Independent variables, range of variation
50.0–2385.0 (34)	310	5.36	SM	$WD = 155.12 + 0.013V_1 + 1.996Z – 212.764PE_2$	0.979	Z 10.0–362.4 V_1 1064–25230 PE_2 0.140–0.821
				$WU = 5.029 – 1.624PE_1 + 0.282ML$	–0.820	PE_1 0.615–2.417 ML 0.99–16.03
				$WD = 121.91 + 3.05Z_1$	0.882	Z_1 2.5–80.6
				$WD = 97.18 + 0.48P_1 + 1.86P_2$	0.967	P_1 130.0–1785.0 P_2 7.5–170.0
63.0–646.0 (24)	160	4.88	W	$WU = 6.964 – 0.483ME_2$	–0.683	ME_2 2.26–13.53
				$WD = 83.54 + 3.74Z_1$	0.773	Z_1 1.0–59.1

Table 8. Individual dairy plants

Plant specification	Mean water consumption *WD* [m^3]	Mean water consumption per unit of final product *WU* [m^3/1000 L]	Season	Multiple regression equation	Correlation coefficient r	Independent variables, range of variation
Type T 4 *P* = 94 kW *ML* = 3.03 kW/1000 L Z_m = 796.4 m^3/month	2221.3 m^3/month	4.29	SM	$WU = 4.3604 – 0.0019Z$	–0.905	Z 19.24–25.10 m^3/d
Type T 1 P = 5420 kW *ML* = 16.5 kW/1000 L *Z* 365.5 m^3/d	1788 m^3/d	5.47	W	$WU = 8,71 – 0.113Z_8 – 0.090Z_9 – 0.235Z_{10} – 0.126Z_{11}$	–0.825	Z_8 3.75–26.45 Mg/d Z_9 5.13–12.54 Mg/d Z_{10} 8.62–16.03 Mg/d Z_{11} 19.25–28.73 Mg/d
Type T 4 P = 1715 kW *ML* = 14.2 kW/1000L *Z* = 120 m^3/d	33242 m^3/month	7.65	SM/W	$WU = 13.268 – 0.0013Z_m$	–0.755	Z_m 3127.3–3476.3 m^3/month

interpretation and correlations with water consumption are shown below.

Daily water demand

Daily water consumption was most highly correlated with the installed capacity of electrical devices (*FR3*). The predominant factors in group *FR3* were power supply departments, boiler plants, pump plants and wastewater treatment devices (P_1 and P_2). Irrespective of the season, the highest correlation was noted in departments *T2* and *T3* in the range of 0.867 to 0.978. This group also contains factor P_3, which accounts for heat exchangers where water is an energy carrier. The methods for increasing the effectiveness of energy carriers in those devices were divided into two groups. The first involves the techniques used at the design stage, including plate profiling and choice of heat exchangers. The second group involves methods that are deployed during device operation, such as controlling the intensity of medium flow and controlling water intake frequency in the cleaning process, as discussed by Kaleta and Chojnacka[58]. Other researchers[59, 60] demonstrated that corrosion of heat exchangers made of acid-proof stainless steel (corrosion-proof) could increase water consumption, in particular in the water chiller system. Pressure in the heat exchanger has to be increased on the milk side to ensure the microbiological purity of the end product, and it can increase water use when exchanger plates are affected by pitting corrosion. Even a minor leakage of dairy products, mainly milk and cream, contaminates the entire chilled water pool which becomes cloudy or milky in appearance. Leaking milk provides a good medium for bacterial growth, and it could be a source of re-infection in pasteurized products. In some cases, the water chilling circuit has to be replenished with fresh water numerous times before the source of the leak is localized. Chilled water systems have a large capacity. Modern water chilling systems have been described by Gliński[61].

The second group of factors which were mostly highly correlated with water consumption is *FR1*. Irrespective of the season, correlations with water consumption were noted only in the group of plants without milk powder departments (*T2*) at r = 0.877 and 0.885. A strong correlation with water consumption (r = 0.979) was reported only in summer in T4 plants characterized by the most limited production profile. This is probably a permanent trend because milk processing profile (*FR2*) was also highly correlated with water consumption (r = 0.882).

The weakest correlation between the analyzed groups of factors and water consumption was observed in plants operating milk powder department. This group of plants (*T1*) supplied 9 products (including items with insignificant influence in regression analysis). One of the factors in group *FR1* is daily milk processing output (*Z*). It can be inferred that in the group of plants without milk powder departments (*T2*), an increase in milk processing output (*Z*) in summer by 1000 l could increase daily water consumption (*WD*) by around 2.62 m^3 in summer and around 4.54 m^3 in winter.

In the discussed type of plants, equipment profiles were most highly correlated with water consumption at r = 0.874 in summer and r = 0.867 in winter. Milk processing output was also highly correlated with water consumption (r = 0.820) in summer during a seasonal peak in production.

Although milk processing output (group *FR2* – Table 3) was the least applicable factor, it was of complementary significance for the previously analyzed groups. The significance of correlations between milk processing output and water consumption increased in summer and with a decrease in the number of supplied products. The above particularly applies to *T3* and *T4* plants where the value of coefficient *r* was determined in the range of 0.773 to 0.900. It can be inferred that an increase in milk processing output by 1000 L in *T3* plants (operating a milk powder department) will increase water consumption by around 2.2 m^3, whereas an increase in butter output by 1 ton will increase daily water demand by around 45.9 m^3. In *T3* plants, group *FR1* factors were highly correlated with water consumption in winter. It can be inferred that in plants with the same cubic capacity of V_2 = 20000 m^3 and total area of S = 18000 m^2, a decrease in the value of indicator *AP* by 45 m^2/1000 l, i.e. by 20%, would increase water consumption (*WD*) by around 3.6% and would decrease water consumption per unit of final product (*WU*) by around 17%.

Based on the value of determination coefficient R^2, the influence of three groups of factors (Table 3) on daily water consumption (*WD*) in the analyzed types of dairy plants (Table 2) in different seasons of the year is presented graphically in Fig. 1 and Fig. 2. Regardless of the season, the examined independent variables effectively explained the variations in water consumption in *T2* and *T3* plants. The results displayed in Fig. 1 indicate that the analyzed factors were increasingly effective in explaining the variations in water consumption with a decrease in the number of supplied products (*FR2* factors). The above can be attributed mainly to longer production series and decreased water consumption for cleaning purposes. A reverse trend was noted in winter (Fig. 2). The presented charts are a more concise form of displaying the results described by regression equations in Tables 4–7. The formulas where high values of R^2 were obtained could be used for modeling water consumption profiles in dairy plants. Problems relating to modeling and optimization of water consumption in the food processing industry have been discussed by Freideler and Varbanov[62] and Peng et al.[63].

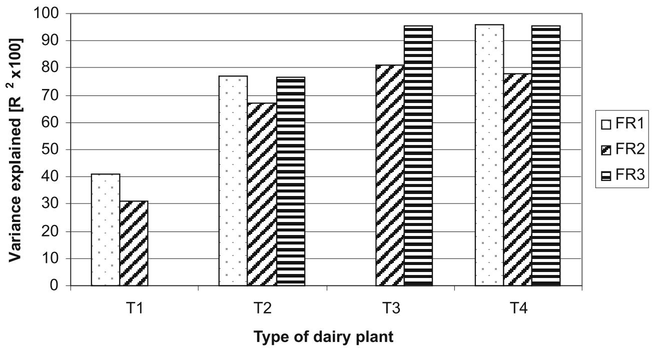

Figure 1. The effect of *FR1*, *FR2* and *FR3* group factors on daily water consumption (*WD*) in summer

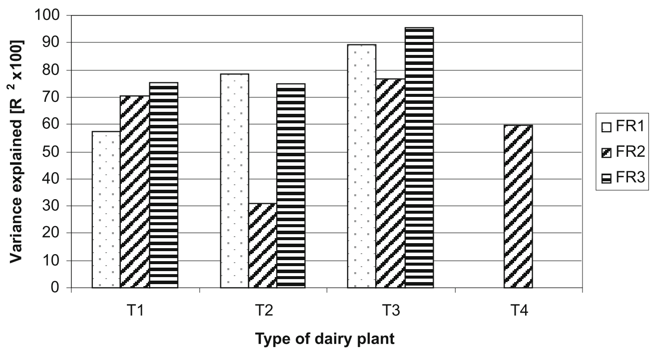

Figure 2. The effect of *FR1*, *FR2* and *FR3* group factors on daily water consumption (*WD*) in winter

Indicators of water consumption per unit of final product

The first group of factors (*FR1*) was most highly correlated with water consumption per unit of final product. In *T3* and *T4* plants, where 0.820 > |r| > 0.663, the following factors were used to develop empirical formulas for *WU*: PE_1 and *ML* (functions of milk processing, selected organizational aspects and utilization of processing capacity) as well as ME_1 and ME_2 (indicators of technical equipment and employment). A detailed analysis of the above equations indicates that an increase in the values of PE_1 and ME_1 lowers water consumption per unit of final product *WU*. The formulas suggest that an increase in the value of ME_2 by one unit (kW/person) in *T3* and *T4* plants could reduce water consumption per unit of final product by around 0.47–0.48 m^3/1000 L of milk. An increase in the processing output of *T4* plants (e.g. when the value of *ML* [kW/1000] is decreased by one unit) led to a decrease in water consumption per unit of final product *WU* by around 0.282 m^3/1000 L of milk. In summer and winter, daily *ML* values were determined in the range of 6–14 kW/1000 L of milk, and they accounted for 57.5% and 71.8% of the total number of analyzed plants, respectively. An increase in the installed capacity of production devices while processing output was kept constant led to an increase in water consumption per unit of final product. The above confirms that *FR3* factors are strongly correlated with water consumption. It can be concluded that the above equations effectively explain the variations in water consumption per unit of final product, and they can be used to analyze industrial trends. The above formulas can also be deployed in the process of designing and analyzing the performance of dairy plants.

The highest level of water consumption per unit of final product *(WU)* was noted in *T1* dairy plants (operating milk powder departments) at 5.50 and 7.57 m^3/1000 L. The above values were not correlated with any of the analyzed factors. In a study by Budny et al.[46], the value of indicator *WU* in a plant with a similar production profile and installed capacity of 1187.4 kW (not listed in Table 4) was determined at 33.24 m^3/mg of milk powder, but the coefficient of correlation *r* between milk processing output and daily water consumption reached only 0.39. Scheltinga[64] reported water usage of 11 L per kilogram of processed milk. In the above study, water consumption per unit of cheese and butter differed 3–5 fold. This group of dairy plants was also discussed by Okoth[65].

It should be noted that the formulas describing variations in water consumption per unit of the final product (*WU)* have fewer applications than those expressing variations in daily water consumption (*WD*) in *T3* and *T4* dairy plants. A detailed specification of conditions in three different plants is presented in Table 8. Individual plants differed significantly with regard to the applied technological solutions (*T1* and *T4*), installed capacity of electrical devices, and values of *ML* which were determined in the range of 3.03 to 16.5 kW/1000 L. *T4* plants were analyzed based on only one factor from group *FR1* (milk processing output – Z or Z_m). In one of the examined *T4* plants, an increase in daily milk processing output by 1000 l decreased the value of factor *WU* by 0.0019 m^3/1000 l. An increase in monthly milk processing output by 1000 L decreased the value of *WU* by around 0.0013 m^3/1000 L. In a *T1* plant, daily milk processing output (*FR2* factor) was highly correlated with water consumption per unit of final product (r = 0.82). The values of different production profile factors (various types of milk powder) point to their varied effect on water consumption per unit of final product. In a *T1* plant, water consumption per unit of final product was similar to the mean value of that indicator in the analyzed group (Table 4). In view of the number of analyzed plants, the results of analyses investigating the correlations between various factor groups and water consumption per unit of final product (*WU*) supplement the data presented in Table 1. The proposed solutions for integrating production processes and applying process water in cooling systems are somewhat analogous to those deployed in brewing, meat processing industries and certain types of fruit and vegetable processing plants. The results of our study can be compared with the findings of Feng et al.[1], Tokos and Novak Pintarič[66], Steinhoff-Wrześniewska et al.[26] and Wojdalski et al.[57] who analyzed the above branches of the food processing industry.

Practical application of water consumption indicators

The results of the surveys carried out in dairy plants indicate that the following measures need to be implemented to maximize the effectiveness of water management and conservation practices:

– selection of the equipment that ensures maximum productive capacity (in particular devices input in equations that express daily water consumption),

– use of additional water meters in devices and production lines characterized by the highest water consumption for detailed and regular monitoring of water consumption per unit of final product,

– implementation of design solutions that support the rational use of the cubic capacity of dairy plants,

– reuse of the condensate from evaporators for cleaning the vehicles, rinsing process equipment and for fire fighting purposes (in particular P_4),

– improved reuse of the condensate (secondary water) for feeding steam boilers,

– implementation of Cleaning-In-Place methods and use of self-locking spray guns (in particular P_3),

– use of closed circuit cooling water systems (in particular P_1 and P_2).

Item P_2 also includes a water treatment plant for water drawn from own wells. The criteria for selecting and operating a water treatment plant have been discussed by Ostrowski and Marjanowski[67]. Ostrowski et al.[68] presented a set of guidelines for improving the reuse of evaporator condensates and permeates from membrane concentration of whey for the needs of:

– membrane cleaning, microfiltration (MF), nanofiltration (NF) and reverse osmosis (RO),

– power systems (boilers),

– cooling systems,

– chilled water supplementation,

– preliminary cleaning in the CIP system,

– cleaning milk tank trucks.

It has been demonstrated that 57 kg of water which meets process water and boiler water requirements can be recovered from the processing of 100 kg of milk. The above is related to the operation of P_4 devices.

Reverse osmosis supports single-stage treatment of:

– condensates from evaporation of milk and whey powder,

– permeates from membrane concentration of sweet (rennet) whey.

Permeates treated by reverse osmosis meet the most qualitative requirements for CIP process water and steam boiler water. The resulting concentrate can be evacuated directly to the waste treatment plant.

The chemical composition of permeates obtained from whey concentration is determined by the type of whey and the applied membrane concentration process. In general, there are two types of whey: sweet rennet whey (from the production of ripening cheese) and acid whey (from the production of cottage cheese). They differ in their content of lactic acid (0.05–0.1% in rennet whey and 0.4–0.7% in acid whey) and minerals, mostly calcium (0.04% in rennet whey and 0.12% in acid whey).

The parameters of degraded water, including reused condensates and permeates, are presented in Table 9.

The presented composition is typical of the degraded water. The temperature of the permeates and conden-

Table 9. Parameters of permeates from membrane concentration of whey and evaporation condensates

Degraded water	Conductivity [μS/cm]	COD [mgO_2/dm^3]	BOD_5 [mgO_2/dm^3]	Lactose [%]	Lactic acid [%]	pH
Acid whey permeate	5000–8000	6000–10000	3000–6000	0.02–0.2	0.02–0.05	4.5–5.0
Rennet whey permeate	200–500	100–400	50–200	trace	0.01–0.02	5.0–6.0
Condensate from milk evaporation	5–50	20–100	5–70	trace	trace	5.0–8.0
Condensate from whey evaporation	20–150	50–300	30–200	trace	trace	5.0–8.0

Source: Ostrowski et al.

Table 10. Practical solutions for reducing water consumption in dairy plants

Measure	Correlation with explanatory variables/Effects
Programming the optimal water demand for CIP	in particular P_3, P_5, Z_1
Using flow meters in CIP circuits and controlling the consumption of water and cleaning agents	in particular P_3
Using sensors to separate rinsing water from cleaning products and agents	P_3, P_4, P_5, P_6, P_7
Checking the condition of the CIP station (including rinsing heads and nozzles)	P_3, P_4, P_5, P_6, P_7
Controlling and optimizing cleaning parameters (temperature, pressure, flow rate of cleaning solutions, time of every cleaning process sequence)	P_3, P_4, P_5, P_6, P_7, V_1, V_2
Adjusting the flow rate and pressure of water and cleaning solutions to the values recommended by the device manufacturer	P_3, P_4, P_5, P_6, P_7, V_1, V_2
Using rinsing heads and nozzles characterized by optimal efficiency and appropriate structure for the cleaned site	P_3, P_4, P_5, P_6, P_7, V_1, V_2
Storing water from the last rinsing session in the CIP system in special tanks and reusing that water in the first rinsing of product remnants from the system	P_3, P_4, P_5, P_6, P_7, P_8, Z_1, Z_3, Z_5
Using pressure foam systems for cleaning floors and external surfaces of process devices	saves up to 60% more water in comparison with traditional cleaning regimes, V_1,V_2
Reducing the quantity of water used for system rinsing	P_3, P_4, P_5, P_6, P_7, P_8, Z_1, Z_5
Using small-diameter water hoses, e.g. 15-25 mm, with self-locking spray guns	P_3, P_4, P_5, P_6, P_7, P_8
Installing flow meters in pipelines distributing water to production, technical, auxiliary departments and employee utility rooms	with special emphasis on P_2, V_1, V_2
Monitoring water usage per unit of raw material, unit of final product or unit of time in every production department, developing water consumption charts for the entire plant or individual production departments, with a division into process water, boiler water and utilities water	with special emphasis on Z_1, Z_2, Z_3, Z_4, Z_8, Z_9, Z_{10}, Z_{11}, V_1, V_2
Using closed water circuit systems, reusing degraded water (e.g. as a heat carrier), implementing technical and process solutions to reduce water consumption and recover rinse water	V_1, V_2, P_4
Inspecting water distribution pipelines, identifying systems and devices where improvements and repairs would contribute to lower water usage	P_1, P_2, P_3, P_4, P_5, P_6, P_7, P_8, V_1, V_2
Repairing leaks from connections, valves and seals, monitoring water consumption outside production hours to identify system leaks, water distribution patterns and determine water consumption levels	in particular P_1, P_2, V_1, V_2
Replacing seals and fast-wearing parts regularly and in accordance with the manufacturer's guidelines	in particular P_3, Z_1

Source: own compilation based on Zander and Dajnowiec[69] and Zander et al.[70].

sates is determined by many factors unrelated to milk processing, therefore, it was not given in Table 9. The observations that could have practical implications for the water management policies of dairy plants are presented in Table 10. Situations which can be encountered in dairy plants and their correlations with the factors given in Table 3 were described. The main technical factors (group *FR 3*, Table 3) and the cubic capacity of dairy plants (V_1 and V_2) (group *FR1*, Table 3) were listed. The selected production factors which were partially correlated with water consumption were also presented.

Similar conclusions and observations were formulated by other authors, among them Baskaran et al.[30], Rausch and Powell[71], and Atkins[39]. The types of production operations and conditions which are correlated with water consumption in the analyzed plants are indicated in Tables 9 and 10. The presented data contribute to the findings of Dvarioniene et al.[42] who investigated the use of clean production technologies in Lithuanian dairy plants. Water management and energy efficiency solutions in dairy plants were also discussed by Brush et al.[72]. Pollutant concentrations in dairy effluents given by Anielak[73], Baras and Jovanović[29], Demirel et al.[32], Ikhu-Omoregbe and Masiiwa[74], Janczukowicz et al.[75], Nadais et al.[76], Özbay and Demirer[77], Rüffer and Rosenwinkel[14], Neryng et al.[55], Talik and Kutera[34] can be used to determine pollutant loads in dairy plants, which is an important environmental consideration. The quantity of the generated wastewater is correlated with water consumption. The results of those analyses can be applied to calculate the BOD_5 values of wastewater and to evaluate the environmental impacts of dairy processing[14, 34, 55, 78]. In a study analyzing the energy effectiveness of wastewater treatment in a dairy plant processing around 150000 l of milk per day, Kowalczyk and Karp[35] relied on indicators expressed in terms of kWh/m^3 of treated wastewater and kWh of the removed pollutant load measured in kilograms of BOD_5 (kWh/kg BOD_5). The above authors demonstrated that 13.6% to 17.3% of the plant's overall energy expenditure went to wastewater treatment when the pollutant load expressed in kilograms of BOD_5 varied from 20.9 to 95.2 kg O_2/h. An increase in pollutant load measured in kilograms of BOD_5 from 20.9 to 95.2 kg O_2/h lowered the energy consumption indicator from 3.22 to 0.89 kWh/kg BOD_5 and the kWh/m^3 indicator from 6.32 to 1.94. The discussed study also demonstrated that a two-fold increase in pollutant load produced a 1.6-fold drop in the energy consumption indicator expressed in kWh/kg BOD_5 and a 1.4-fold decrease in the value of the indicator expressed in kWh/m^3. In the analyzed waste treatment plant, nearly 80% of electricity was consumed to keep the facility in operation regardless of the effluent stream. Around 85% of total energy was used to aerate wastewater. The above data clearly indicate that research results can be translated into effective practical applications because factor P_2, which comprises water and sewage pumping plants and the wastewater treatment plant, was applied in regression equations for *T2*, *T3* and *T4* plants (Tables 5–7). It should also be noted that due to the variety and complexity of individual processes, mathematical forecasts of pollutant loads in dairy wastewater can be burdened with error. The results of this study can be used to supplement and update BAT reference materials for the dairy industry[39]. The savings generated by reduced consumption of water were discussed by Williams and

Anderson[79]. Detailed information about water saving measures can also be found in the Energy Performance Indicator Report[36]. The analyzed indicators can be used to develop methods for evaluating the environmental footprint of production plants, as discussed by Maxime et al.[80], and for comparative analyses of studies by Wendorff[81] and Perry[82]. In the context of environmental protection, our results can contribute to life cycle analyses (LCA) of dairy products which were carried out by Berlin[83] and Thomassen et al.[84].

CONCLUSIONS

The following conclusions can be formulated based on the results of this study:

– water consumption was most highly correlated with dairy plants' equipment profiles (r > 0.868), which calls for the need to implement design solutions that optimize dairy plants' demand for this energy carrier,

– dairy plants producing milk powder (*T1*) were the largest consumers of water. In addition to milk powder, those plants supplied eight other dairy items, therefore any organizational improvements (water reuse for cleaning process lines and auxiliary purposes) in the production process could contribute to a significant decrease in water consumption

– in plants producing fewer dairy items, the production profile were more correlated with water consumption per unit of final product,

– cubic capacity, total installed capacity of electrical devices and daily processing output of *T2* dairy plants (not producing milk powder) were highly correlated with water consumption (r = 0.877),

– water consumption per unit of final product was correlated with the equipment profile, process automation and employment only in smaller plants producing fewer dairy items,

– in individually examined plants, water consumption per unit of final product was highly correlated with both milk processing output and production profile,

– the developed empirical formulas, in particular indicators of water consumption per unit of final product, can be used in detailed analyses, they can supplement data bases, reference materials and contribute to the development of water consumption models in dairy plants,

– in view of the structure of independent variables, the presented formulas can also be used to optimize water usage in various types of production equipment and to determine correlations between water consumption and energy use in wastewater treatment systems,

– the presented results can contribute to an improvement in water management standards and the implementation of hygiene standards in the dairy industry by reducing or optimizing water demand in dairy plants.

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Symbols and abbreviations

$AP = S\,Z^{-1}$ – dairy plant area per 1000 L of milk processed in 24 h [m^2/1000 L];
BAT – Best Available Techniques,
FR – groups of factors (*FR1, FR2, FR3*) related to water consumption in dairy plants (presented in this list and in Table 3)
$ME_1 = P\,N_1^{-1}$ – installed capacity relative to the number of production employees [kW/person];
$ME_2 = P\,N_2^{-1}$ – installed capacity relative to the total number of employees [kW/person];
$ML = P\,Z^{-1}$ – installed capacity per 1000 L of milk processed in 24 h [kW/1000 L];
$PE_1 = Z\,N_1^{-1}$ – daily processing output per production employee [m^3/person];
$PE_2 = Z\,N_2^{-1}$ – daily processing output per plant employee [m^3/person];
N_1 – number of production employees;
N_2 – total number of employees;
P – otal installed capacity of electrical devices in the plant [kW];
P_1 – installed capacity of the machine unit of the cooling system and the compressed air station, [kW];
P_2 – installed capacity of the boiler plant, hydraulic accumulator unit, water treatment station, water and effluent pumping station and wastewater treatment station [kW];
P_3 – installed capacity of raw material receiving area, heat exchangers, centrifugal pumps, homogenizing units, storage tanks, cleaning stations, filling lines [kW];
P_4 – installed capacity of milk condensing and evaporating units [kW];
P_5 – installed capacity of the casein production department [kW];
P_6 – installed capacity of the butter production department and butter packaging machines [kW];
P_7 – installed capacity of repair workshops and the maintenance department [kW];
P_8 – installed capacity of other power receivers [kW];
r – correlation coefficient;
R^2 – coefficient of determination [r^2];
S – total area of dairy plant [m^2];
T – types of investigated dairy plants (*T1, T2, T3* and *T4* – based on their production profile) defined in Table 2;
V_1 – cubic capacity of the plant's production units [m^3];
V_2 – cubic capacity of the plant's production and auxiliary units [m^3];
WD – daily water consumption [m^3];
$WU = (WD)Z^{-1}$ – water consumption per unit of final product [m^3/1000 L milk];
Z – daily milk processing output [m^3/d];
Z_m – monthly milk processing output [m^3/month];
Z_1 – production of milk, dairy drinks and cream [m^3/d];

Z_2 – milk input in cottage cheese production [m^3/d];
Z_3 – milk input in cheese production [m^3/d];
Z_4 – milk input in milk powder production [m^3/d];
Z_5 – milk input in casein production [m^3/d];
Z_6 – milk input in feedstuff production [m^3/d];
Z_7 – butter production [t/d];
Z_8 – production of the skimmed milk powder [Mg/d];
Z_9 – cheese production [Mg/d];
Z_{10} – production of whey powder [Mg/d];
Z_{11} – production of the whole milk powder [Mg/d].

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