USAGE OF BIOSURFACTANTS AS ENVIRONMENTAL FRIENDLY DETERGENTS FOR TEXTILE PRODUCTS CLEANING

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ABSTRACT

The paper is devoted to the resource-saving technologies of cleaning the textiles in the aquatic environment. As a resource-saving technology the use of biosurfactant compositions replacing traditional detergents was chosen. These technologies are characterized by high quality cleaning the textile garments, reduced time of operations, reduction of the costs of chemicals and energy, improvement of environmental safety of the process and and also allow to extend the shelf life of products.

Resource-saving cleaning technologies (washing, aqua cleaning) have been improved and recommendations for their application have been developed, considering changes in the operational properties of new generation textiles, which will extend the service life of new generation textiles, save operational properties, enable their eco-recycling (reuse) and reduce the impact on the environment and human health through the use of biosurfactant compositions. Innovative compositions of biosurfactants with a synergistic effect in micelle formation were elaborated. Steric factor associated with the rational packaging of biosurfactants molecules in mixed micelles, as well as the possibility of forming micelles of optimal composition can influence synergistic effect. The use of elaborated compositions of biosurfactants in washing processes offers several environmental and health advantages.

The complex research of influencing parameters of chemical-technological processes and properties of washing compositions on the basis of correlations the products of new generation were developed that provides improvement of quality of removal of contaminations from textiles and process safety. It is proved that the application of the developed resource-saving technologies saves 10 liters of water per cleaning cycle, 0.0348 kWh of electricity, and 0.142 hours of working time.

KEYWORDS

Resource-saving technologies; Cleaning; Wet cleaning; Laundry; Textiles; Bio-surfactants.

INTRODUCTION

Textile products are an integral part of people's routine life. During the use of textile products, the human body has direct contact with textile materials during the whole life. Therefore, today the issue of safety of textile materials and clothing is particularly important in manufacturing and exploitation. Modern textile materials and products, in terms of their impact on human health, are a source of potential exposure to a range of factors: the nature of raw materials, the characteristics of their production processes, and finishing agents [1, 2]. In recent years, there have been significant changes in the range of products, and we can witness a tendency towards the manufacturing of new generation textile materials with additional properties, which in most cases are considered by consumers as the main arguments in favour of purchasing goods [3, 4]. At the same time, a large amount of textile waste is generated every year due to the wear-out, deterioration of consumer properties of textile products during their usage and frequent laundering. In addition, there are substantial difficulties in choosing a cleaning technology for new generation textiles, as existing technologies are not effective enough for such products.

Currently, the textile industry is rapidly developing, the range of textile products is changing, new products for their cleaning are emerging, the cost of energy and material resources is growing, environmental and consumer requirements and the quality of cleaning services are getting higher. Therefore, the existing technologies for cleaning textiles in the aqueous environment need to be updated and improved in accordance to the modern requirements and consumers' demands [3-6].

Textile cleaning processes consist of sequential operations: washing, extraction, drying and ironing. Washing is the main operation in the technological

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cycle that restores the physical and hygienic properties of products.

When choosing technological processes for cleaning textile products, it is necessary to take into account the specifics of their range and processing modes, which will ensure high service quality for consumers, save the operational properties of new generation products, and extend their service life. Currently, textile cleaning technologies provide a wide range of services to consumers: washing, cleaning clothes, removing stains, ironing, garment repair, preserving fur products, and treatment of garments to prolong the cleanliness of products and protect them from pathogenic bacteria. High-quality cleaning of textile materials and products is achieved through the use of the latest technologies combined with effective detergents [7-9].

Synthetic detergent is difficult to be degraded by bacteria in water, so detergent waste remains in the water; therefore, the accumulation of the amount of detergent in water occurs. The accumulation of detergent in water can be a source of pollution in the water stream. Concerns over the persistence of detergent chemicals in the environment and possible contamination of groundwater, other surface water sources also their subsequent health-related issues have raised speculation over biodegradability. The shift to an era of more environmentally friendly products has encouraged the industry to create environmentally friendly detergents. The solution to this problem can be overcome by using surfactants made from oleochemicals and other bio-based products.

That is why this paper deals with replacement of synthetic detergents by biosurfactants. Innovative compositions of biosurfactants with a synergistic effect in micelle formation were elaborated. Steric factor associated with the rational packaging of biosurfactants molecules in mixed micelles, as well as the possibility of forming micelles of optimal composition can influence on synergistic effect. The use of elaborated compositions of biosurfactants in washing processes offers several environmental and health advantages. Biosurfactants are generally considered to have lower toxicity than synthetic surfactants. This can be beneficial for both environmental and human health. Biosurfactants tend to have lower ecotoxicity, making them less harmful to aquatic organisms when discharged into water bodies. Biosurfactants exhibit versatile properties and can be effective in various washing processes, including laundry detergents and household cleaners. Innovative compositions of biosurfactants can be produced from renewable resources, such as plant oils, contributing to sustainability.

The main goals of this research are to improve resource-saving technologies for cleaning textile products of the new generation, which are based on the creation of innovative highly effective detergent compositions using biosurfactants. This will allow to improve the quality of product processing, environmental safety of the process, extend the service life of products, and reduce the cost of cleaning industry services.

The technological characteristics of the technologies for cleaning products in an aqueous environment are shown in Table 1.

Thus, textile cleaning processes are characterized by multifactoriality and complexity. An analysis of modern textile cleaning processes has shown that they have a number of disadvantages, including possible damage to products, the risk of chemical contamination of wastewater, expensive services, and significant electricity and water consumption [4, 6, 8, 10]. Therefore, the development of resource-saving technologies for cleaning textiles is an important task for the textile industry, the cleaning and service industry, and solving it will help improve the quality of the new generation of products cleaning, extend their service life, reduce the environmental impact and the cost of services. Resource-saving technology refers to innovations and practices that aim to minimize the use of resources such as energy, water, raw materials, and time, while maximizing efficiency and reducing waste. These technologies play a crucial role in sustainable development and environmental conservation. The implementation of resource-saving technologies is crucial for achieving sustainable development goals, mitigating environmental impact, and creating a more resilient and efficient global infrastructure.

EXPERIMENTAL PART

Materials used

Studies of the efficiency of chosen biosurfactant compositions for cleaning the textile garments in the aquatic environment were performed on specimens of cotton, polyester and mixed fabrics, which are presented on the market of Ukraine (Table 2).

The experimental samples were treated with the developed compositions containing biosurfactants [11, 12]. The composition and basic colloidal and chemical properties of the developed biosurfactant compositions are given in Table 3. CMC is critical micellar formation concentration, was determined by plotting the equilibrium surface tension against the surfactant concentration, σ - surface tension was measured by capillary rice method, θ is wetting edge angle evaluated by the static (sessile) drop contact angle (it is defined geometrically as the angle formed by a liquid at the three-phase boundary point where a liquid, gas, and solid intersect), H is the foam height, S is foam stability established by the Ross-Miles method according to ASTM D 1173. Barvamid 2K according to TU U24.1-32257423-118:2005 is an acetic acid salt of the product of the interaction of the

Table 1. Technological characteristics of product cleaning technologies in an aqueous environment.

Washing	Aqua-cleaning
Recommended only for underwear and hospitality products	Recommended for garments, textile products for the household
Drum rotation speed when washing textiles	
Fixed 36 or 40 revolutions per minute	Adjustable from 5 to 40 revolutions per minute
Drum rotation speed when extracting textiles	
Fixed 400 or 500 revolutions per minute, rigid fixation of the drum	Adjustable from 400 to 1000 revolutions per minute, drum on springs and shock absorbers
Drum rotation/stop time when washing textiles	
Fixed rotation time 12 s or 20 s, stop time 3 s or 4 s	Adjustable rotation time from 0.1 s to 90 s, stop time from 0.1 s to 90 s
Water temperature when washing textiles	
Varies from cold to 90℃	Varies from 27℃ to 40℃
Water level	
Varies between high and low	Varies gradually (from ml to l), from high to low
The amount of textile washing	
From 1 to 3	Typically 1, for highly contaminated products 2
Duration of washing in one bath	
5 min to 20 min (without heating)	4 min to 10 min (with heating)
The number of rinses	
3 or more rinses	1 rinse
Drying temperature for textile products	
From 50℃ to 110℃	From 40℃ to 60℃
Detergents used in the process	
Washing powders, soaps, bleaches	Liquid detergents, softeners

Table 2. Parametrs of the studied textiles materials.

The name of the fabric	Width [cm]	Density		Warp, Weft		Weave	Areal density [g/m^2]
		Weft [wefts/cm]	Warp [warps/cm]	Yarn linear density [tex]	Material composition		
Fabric 1 100 % cotton	150±5	22	41	30	$(C_6H_{10}O_5)_n$	plain-weave	180
Fabric 2 80% cotton, 20 % polyester	150±2	22	41	30	80 % $(C_6H_{10}O_5)_n$, 20 % $(C_{10}H_8O_4)_n$	plain-weave	220
Fabric 3 65 % cotton, 35 % polyester	150±2	22	41	30	65 % $(C_6H_{10}O_5)_n$, 35 % $(C_{10}H_8O_4)_n$	plain-weave	220
Fabric 4 100% polyester	150±2	22	41	30	$(C_{10}H_8O_4)_n$	plain-weave	220

Table 3. Composition and basic colloidal and chemical properties of the developed biosurfactant compositions.

Biosurfactant	Composition, *W*, [%]	*CMC*, [M]	*σ*, [mN/m]	*θ*,[°]	*H*, [mm]	*S*, [%]
Composition 1	67 % DEA cocamide, 33 % biguanidine derivative	$2.5·10^{-4}$	38.18	19.15	14	56
Composition 2	80 % barvamid 2K. 20 % sulphonol NP-3	$4·10^{-4}$	32.15	15.98	13	92
Composition 3	67 % barvamid 2K, 33 % stearox 920	$1.0·10^{-4}$	35.63	35.75	14	85

Table 4. Initial data for the five-factor experiment according to the Hartley plan.

The name of the factor	The factor	Levels		
		-1	0	+1
Solution concentration of compositions biosurfactants, [g/l]	X_1	1	3	5
The liquid module	X_2	8	10	12
Temperature, [℃]	X_3	20	30	40
Processing time, [min]	X_4	2	5	8
Extraction [revolutions per minute]	X_5	400	700	1000

cubic residue of β-oxyethylethylenediamine and higher fatty acids of coconut oil and stearox 920 is a mixture of polyoxyethylene glycol esters of stearic acid.

Research methods

In order to mathematically describe the dependences of the technological parameters of the process of cleaning textile products and to rationally conduct research, the method of planning experiments was applied Hartley plan. The determination of the most significant factors on the operational properties ow washing process (using biosurfactants) was carried out using the five-factor experiment according to the Hartley plan [13, 14]. The coded values of the factors that have the most impact on the finishing process and their levels are given in Table 4. For this experiment the biosurfactant marked Composition 1, Composition 2, Composition 3 was used.

The homogeneity of the dispersions was checked by the Cochrane criterion: the dispersions for each experiment are homogeneous. The adequacy of the obtained mathematical models was checked by Fisher's criterion.

Analysis of the results of the experiment made it possible to obtain the coefficients of a polynomial that establishes the correlation between all factors of the technological process of cleaning textiles and the detergent (biosurfactant) effect. The analysis of the obtained coefficients allows us to exclude from the final expression the coefficients with values less than the critical ones. Accordingly, the regression equations of detergent action for the studied fabric samples in coded values were obtained. The washing effect regression equation for the investigated tissue samples in coded values $Y(X_1, X_2)$ was obtained:

Fabric 1: 100% cotton:

$$Y=79.952-0.163X_1-0.059X_2+0.052X_3-0.374X_1^2-0.121X_2^2-0.144X_1X_2 \quad (1)$$

Fabric 2: 80 % cotton, 20 % polyester:

$$Y=79.952-0.163X_1-0.059X_2+0.052X_3-0.374X_1^2-0.121X_2^2-0.144X_1X_2 \quad (2)$$

Fabric 3: 65 % cotton, 35 % polyester:

$$Y=74.009-0.183X_1-0.044X_2+0.067X_3-0.347X_1^2-0.115X_2^2-0.205X_1X_2 \quad (3)$$

Fabric 4: 100% polyester:

$$Y=76{,}112-0{,}185X_1-0{,}016X_2+0{,}046X_3-0{,}361X_1^2-0{,}178X_2^2-0{,}107X_1X_2 \quad (4)$$

Analysis of these equations allows us to come to several conclusions. This polynomial is a paraboloid. Considering the signs of the coefficients before X_1 and X_2, this paraboloid is directed down the Z-axis, and with the growth of X_3, the maximum value is continuously increasing. Moreover, as X_3 increases, the value of the maximum detergent action Y (washing effect) will also increase. According to the results of the optimization, it was found that the factors that affect washing have different effects on the cleaning process of cotton, polyester and mixed fabrics. When washing cotton fabrics, all three investigated factors were found to be significant. On the other hand, when washing PES fabrics, only two factors were found to be significant: the concentration of the composition in the solution and the modulus of the bath. In general, cotton materials are washed better in an aqueous environment from hydrophobic contamination than PES ones. The study on the redeposition of contaminants showed that the concentration of biosurfactants in the solution is a significant factor.

The washing parameters: washing ability (*WA*, [%]) and redeposition (*RD*, [%]) ability was determined by the photometric method SNI ISO 105-C06:2010 by fabric whiteness [15]. The white color fabric samples were cut into 5x10 cm rectangle and each of them was polluted by complex pollution. The fabric samples were removed by the resource-saving technology using different biosurfactant compositions, see Table 3.

The washing ability (*WA*, [%]) was calculated according to the equation:

$$\boldsymbol{WA} = \frac{(K/S)_d-(K/S)_c}{(K/S)_d-(K/S)_0} \times \mathbf{100}\ \% \quad (5)$$

where $K/S = \frac{(1-R)^2}{2R}$; R – the intensity of reflection of monochromatic light from samples; K – the coefficient of light reflection from the fabric sample; S – the light scattering coefficient; $(K/S)_0$ – the coefficient of light reflection from the original fabric sample; $(K/S)_d$ – the coefficient of light reflection from the contaminated fabric sample; $(K/S)_c$ – the coefficient of light reflection from the fabric sample after cleaning in an aqueous environment.

The redeposition capacity of biosurfactant compositions (*RD*, [%]) was calculated according to the formula:

$$\boldsymbol{RD} = \frac{R_0-R_{REFL}}{R_0} \times \mathbf{100}\% \quad (6)$$

where R_0 – the coefficient of light reflection from the original fabric sample; R_{REFL} – the coefficient of light reflection from the fabric sample after cleaning in an aqueous environment.

The change in mechanical properties of fabrics after cleaning in the aquatic environment was determined according to standard methods DSTU ISO 13938-1:2007, DSTU ISO 13938-2:2007 [16, 17].

The assessment of the change in the mechanical properties of cellulosic materials was carried out according to the indicators of bursting strength P_p, [N] and bursting distension l_p, [mm].

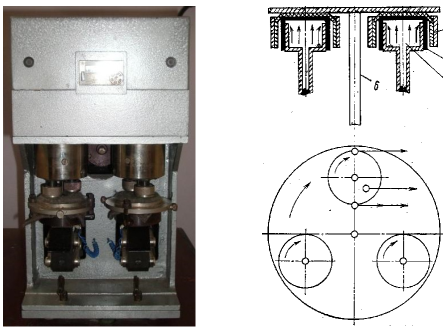


Figure 1. The external and schematic view of the IT-ZM-1 device.

To define the abrasion resistance of textile material samples, we used the durability characteristic - the number of abrasion cycles before the formation of holes. To define the resistance of textile materials to abrasion in laboratory conditions, the IT-ZM-1 device was used (Fig. 1).

Elementary specimens shaped like circles with a diameter of 27 mm were inserted into the runner holders with the front side up. A prepared 95 mm wide strip of overcoat fabric was inserted into the hoop, on which a ring was placed and secured with screws. A metal ring was placed on the fabric and the sample was fixed on the hoop using a 25 mm diameter abrasive wheel clip. After filling the fabric and abrasive in the hoop, the device was switched on. After the device was stopped, the number of rotation cycles at which the fabric surface was destroyed was recorded.

All measurements were repeated 10 times (n=10). Mean values together with 95% confidence intervals are shown to enable comparison of sample properties after multiple washing in an aqueous environment.

In order to study the energy characteristics of modern washing equipment, an experimental bench was used to determine the necessary parameters of the technological process of cleaning textile products in an aqueous environment. A block diagram of the study of operational indicators of the implementation of resource-saving technologies for cleaning textile products in an aqueous environment is shown in Fig. 2.

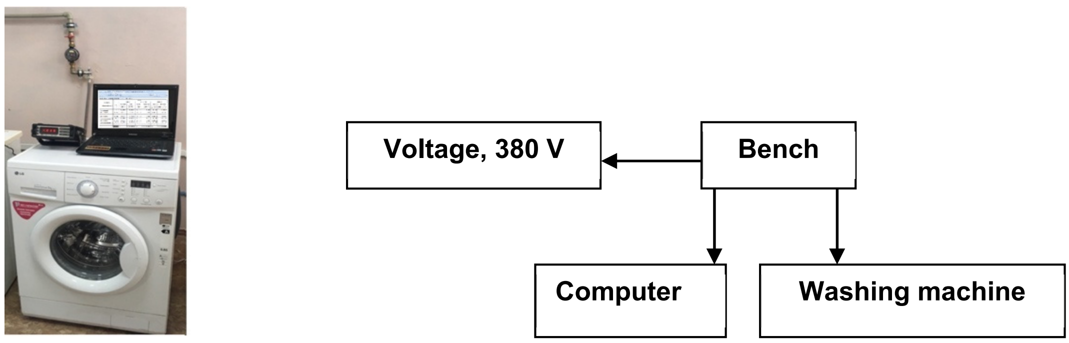
RESULTS AND DISCUSSION

Technological processes for textile cleaning consist of sequential operations: washing, extraction, drying and ironing. The results of optimizing the process of textile cleaning according to detergent (biosurfactant) action, antiresorption capacity, capillarity and stiffness for samples of cotton, polyester and their combinations made it possible to obtain optimal values of the technological parameters of the process of textile cleaning of various assortments: composition concentration from 2.5 to 3 g/l; bath module 10; processing temperature from 20 to 30 ℃; processing time 8 min; extraction 400 revolutions per minute. Three types of biosurfactants (table 3) were applied and their effect on cleaning (washing and aqua-cleaning) of textiles in the aquatic environment was studied.

Tables 5-7 show different steps for washing and aqua-cleaning of textiles using biosurfactants.

According to Tables 5 - 7, the time required for operations is reduced from 18 to 38 minutes, as well as the processing temperature is reduced from 10 ℃ to 30 ℃ by one cleaning cycle, compared to the typical technology (Table 1) of cleaning products.

In order to evaluate the effectiveness of textile products cleaning using biosurfactants, the washing performance parameters (*WA*, *RD*, [%], according to: Eq. 1, 2) of the developed compositions (Table 3) were compared with similar indicators of detergents (Unix Klin A, Tuono Blu, Lanadol Aktiv, Amway Home SA8), which are widely used in product processing enterprises and in household conditions using technological parameters of washing specified in Table 5. The results of the research are given in Table 8.



(a) (b)

Figure 2. Image and flowchart for defining equipment operational parameters: (a) general view; (b) bench diagram.

Table 5. Technological steps for washing combined fabrics.

The name of operation	t, [℃]	Liquid module	Compositions of biosurfactants	Processing time, [min]
First washing	30	10	+	8
Second washing	30	10	+	8
First rinse	30	12		3
Second rinse	30	12		3
Final processing (treatment)	30	10	+	6
Total duration without final processing with final processing				 22 28

Table 6. Technological steps for aqua-cleaning of mixed fabrics.

The name of operation	Temperature, [°C]	Process/pause, [s]	Rotation speed, revolutions per minute	Processing time, [min]
Washing with the biosurfactant	30	5/10	20	3
Drain	-	5/10	30	0.5
Rinse	30	5/10	30	3
Drain	-	13/4	40	0,5
Extraction	-	-	400	2
Total duration				9

Table 7. Resource-saving technology for aqua-cleaning of mixed highly contaminated fabrics.

The name of operation	Temperature, [°C]	Process/pause, [s]	Rotation speed, revolutions per minute	Processing time, [min]
Washing with the biosurfactant	30	5/10	30	3
Drain	-	5/10	30	0.5
Washing with the biosurfactant	30	5/10	30	3
Drain	-	13/4	40	0.5
Rinse	30	5/10	30	3
Drain	-	13/4	40	0.5
Extraction	-	-	400	3
Total duration				13.5

Table 8. Washing parameters of the developed compositions biosurfactants (washing ability (*WA*, [%]) and redeposition (*RD*, [%]) ability.

Compositions	Fabric 1 (100 % cotton)		Fabric 2 (80% cotton, 20 % polyester)		Fabric 3 (65 % cotton, 35 % polyester)		Fabric 4 (100% polyester)	
	WA, [%]	*RD*, [%]	*WA*, [%]	*RD*, [%]	*WA*, [%]	*RD*, [%]	*WA*, [%]	*RD*, [%]
Compositions biosurfactants 1	83.6	13.3	81.6	15.5	80.1	14.2	77.8	17.7
Compositions biosurfactants 2	76.3	14.1	73.9	14.5	77.4	13.9	75.7	15.6
Compositions biosurfactants 3	80.5	14.7	79.2	15.4	79.8	15.3	80.9	16.1
Unix Klin A	80.0	17.4	76.2	19.1	76.9	20.2	73.8	21.7
Tuono Blu	72.8	23.5	73.3	22.1	73.2	24.4	72.3	23.1
Lanadol Aktiv	80.1	22.2	75.8	20.9	78.4	21.0	74.4	21.1
Amway Home SA8	79.9	25.0	76.3	19.3	77.2	21.1	73.5	22.1

Studies have shown that the highest washing ability was realized by Biosurfactant 1 on Fabric 1 (cotton), Fabric 2 (80% cotton, 20 % polyester) and Fabric 3 (65 % cotton). The highest washing ability for the 100 % PES fabric was provided by Biosurfactant 3. All traditional detergents have lowest washing ability compared to highest washing ability performed by Biosurfactant.

Products with a high content of cotton (Fabric 1, Fabric 2) are best cleaned, while dirt from polyester fabric is less effectively removed, which is explained by the affinity of cellulose fibers to the aqueous environment and the hydrophobicity of polyester products. Using Biosurfactants the redeposition capacity is significantly lower compared to usage of traditional detergents regardless of the material composition of the sample.

The use of the developed biosurfactant compositions can reduce the cleaning cycle by one rinse. However, in the presence of remaining particles of the detergent-soiling complex, with insufficient rinsing, greying of products is possible. Therefore, according to Eq. 2, the redeposition capacity (*RD*, [%]) of the developed compositions was additionally defined by reducing the cleaning cycle of fabrics by one rinse [8, 15]. The results of the study are presented in Table 9.

The study of the antiresorption ability of the developed biosurfactant compositions (Table 8) showed that the quality of textile cleaning of various types of fabrics does not deteriorate with a reduced number of rinses.

It should also be considered that reducing the washing cycle by one rinse reduces the duration of the process, electricity and water consumption, and wages for staff.

Previous studies have shown that the developed biosurfactant compositions should be used for cleaning and finishing of textile products for special and household purposes, which contributes to the proper care of products, removes static electric charges, increases the efficiency of removing contaminants from the surface of fabrics, reduces re-contamination of products, extends their service life, and imparts antimicrobial properties to products [11, 12].

Thus, the implementation of the developed technologies reduces the consumption of reagents, shortens the time of operations, the processing cycle of products, and improves the environmental safety of the process.

The effectiveness of the implementation of the developed technologies for the maintenance of operational properties was evaluated by the semi-cycle characteristics of wear resistance. The results of determining the semi-cycle bursting characteristics (bursting strength, P_p, *N*, bursting distension, l_p, [%]) of textile material samples after multiple washing in an aqueous environment are given in Table 10.

According to the results of the study, the bursting strength of the tested fabric samples after 30 cycles of cleaning is 600 N on the warp and 225 N on the weft for Fabric 1, 850 N on the warp and 600 N on the weft for Fabric 2, 1200 N on the warp and 1100 N on the weft for fabric 3, 1800 N on the warp and 1700 N on the weft for fabric 4. After 30 cycles of cleaning in an aqueous environment according to a typical technology (Table 1), partial destruction and destruction of cotton fabric occurs.

The abrasion resistance (number of cycles) on the surface of the studied samples of fabrics made of cotton, polyester and their combinations after multiple cleaning in an aqueous environment is given in Table 11.

According to Table 9, a similar tendency is observed for the wear resistance of the test samples after multiple cleaning in an aqueous environment. For the cotton fabric sample, partial destruction of the material occurs after 30 processing cycles using a typical technology. Combined and synthetic fabrics made of polyester fibres have greater wear resistance. Thus, the implementation of the developed technologies achieves high quality cleaning of products, increases the number of cleaning cycles compared to the typical technology, and extends the service life of products [6, 8, 10].

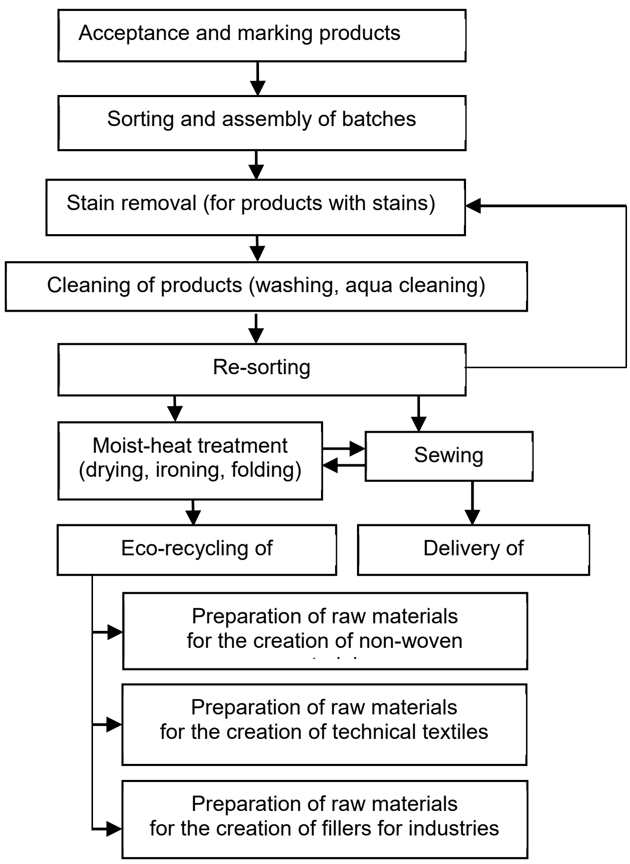


Figure 3. The technological scheme for cleaning textile products in an aqueous environment considering the eco-recycling operation.

In addition, due to the antimicrobial effect of composition 1 (67 % DEA cocamide, 33 % biguanidine derivative), disinfection and eco-recycling of worn products, which are raw materials for the creation of nonwovens, fillers, and technical textiles, is possible [11, 18, 19]. The technological scheme for cleaning textile products in an aqueous environment, considering the reuse of worn textile products, is shown in Fig. 3.

The implementation of eco-recycling of worn-out textiles in the technological process of cleaning products will help reduce the generation of textile waste, processing time in the preparation of raw materials for the reuse of textiles, and create safe reusable textile raw materials.

The cost of processing products at cleaning and service companies depends on the cost of energy, utilities, cleaning products, equipment maintenance costs, staff salaries, and the time required to process products [1, 5, 19, 20].

The summarized results of the efficiency of the implementation of the developed resource-saving technologies for cleaning textile products in the aqueous environment in comparison with the typical technology are given in Table 12.

Thus, with a reduction in the number of rinses per washing, water savings are 10 litres, working time savings are 0.142 hours, and electricity savings are 0.0348 kWh.

Table 9. Redeposition capacity (*RD*, [%]) of washing using biosurfactant compositions.

The number of rinses	Fabric 1 (100 % cotton)	Fabric 2 (80 % cotton, 20 % polyester)	Fabric 3 (65 % cotton, 35 % polyester)	Fabric 4 (100 % polyester)
Composition 1 (67 % DEA cocamide, 33 % biguanidine derivative)				
3 rinses	13.3	15.81	14.83	17.2
2 rinses	13.2	15.28	13.79	17.2
Composition 2 (80 % barvamid 2K, 20 % sulphonol NP-3)				
3 rinses	15.01	15.25	14.95	15.62
2 rinses	14.85	15.25	14.80	15.55
Composition 3 (67 % barvamid 2K, 33 % strearox 920)				
3 rinses	14.75	15.45	15.85	16.5
2 rinses	14.55	15.00	15.55	16.25

Table 10. Half-cycle bursting characteristics of the studied textile materials.

The sample of material	Untreated fabric		Developed technology		Typical technology	
			30 cleaning cycles			
	warp	weft	warp	weft	warp	weft
Bursting strength, P_p, [N]						
Fabric 1 (100 % cotton)	655±14.52	245±5.75	600±12.7	225±5.55	Partial fabric destruction	
Fabric 2 (80 % cotton, 20 % polyester)	870±19.29	630±13.6	850±18.8	600±11.71	800±17.7	590±13.07
Fabric 3 (65 % cotton, 35 % polyester)	1235±27.3	1140±25.3	1200±20.3	1100±24.4	950±21.1	1050±23.28
Fabric 4 (100 % polyester)	1800±39.9	1700±37.7	1800±39.9	1700±37.7	1800±39.9	1700±37.7
Bursting distension, I_p, [%]						
Fabric 1 (100 % cotton)	14±0.35	28,5±0.71	18±0.45	11±0.28	Partial fabric destruction	
Fabric 2 (80 % cotton, 20 % polyester)	25±0.63	41±1.03	25±0.63	39±0.98	20±0.50	32±0.80
Fabric 3 (65 % cotton, 35 % polyester)	33±0.83	46.5±1.16	32±0.80	43±1.08	30±0.75	40±1.00
Fabric 4 (100 % polyester)	45±1.12	47.5±1.19	50±1.25	48±1.20	48±1.20	47±1.18

Table 11. Abrasion resistance of the studied samples, cycles.

The sample of material	Untreated fabric	Developed technology	Typical technology
		30 cleaning cycles	
Fabric 1 (100 % cotton)	4550	4000	Fabric destruction
Fabric 2 (80 % cotton, 20 % polyester)	5200	5000	4500
Fabric 3 (65 % cotton, 35 % polyester)	8200	8000	7500
Fabric 4 (100 % polyester)	8600	8500	8000

Table 12. Summarised results of the efficiency of implementation of the developed resource-saving technologies for cleaning textile products.

Costs	Typical washing technology	Resource-saving washing technology using biosurfactants	Cost savings
Water consumption	48 l	38 l	10 l
Energy consumption	0.2205 kWh	0.1857 kWh	0.0348 kWh
Time commitment	1.085 hours	0.943 hours	0.142 hours

CONCLUSION

The article proposes optimal conditions for the implementation of resource-saving technologies using biosurfactants to improve the efficiency of the technological processes of washing, aqua-cleaning, and finishing of textile products. The developed resource-saving technologies for cleaning textile products are characterised by reduced time of operations, reduced cycle of cleaning products, reduced consumption of reagents, and improved environmental safety of the process.

It was proved that the usage of biosurfactant increases washing ability and at the same time decreases the redeposition capacity of all tested samples compared to usage of traditional detergents. The biosurfactant marked Compositon 1 offers the highest wasthing ability of cotton based textiles even in mixture with polyester. Biosurfactant marked Composition 3 provides the highe washing ablitity for 100 % PES fabrics.

It has been confirmed that due to the efficiency of the developed biosurfactant compositions Table 3 [11, 12], it is possible to reduce the cleaning cycle by one rinse without compromising the quality of cleaning of textile products of various assortments. Recommendations for the use of the developed biosurfactant compositions Table 3 [11, 12] in the technological processes of textile processing are given. It is substantiated that it is not recommended to exceed the working concentrations of the developed compositions more than in the range from 2 to 3 g/l for effective use in the cleaning process. The implementation of the developed technologies ensures a reduction in the time of operations from 18 to 38 minutes, as well as a decrease in the processing temperature from 10 °C to 30 °C, compared to the typical technology of cleaning products, by one processing cycle, respectively. The energy parameters of the equipment are determined, it is proved that by reducing the number of rinses per washing, water savings are 10 litres, working time savings are 0.142 hours, and electricity savings are 0.0348 kWh.

The implementation of eco-recycling of worn-out textiles in the technological process of cleaning products will help reduce the generation of textile waste, reduce processing time when preparing raw materials for the reuse of textiles, and create safe textile raw materials for nonwovens, technical textiles, geotextiles, and the needs of various industries.

REFERENCES

1. Salerno-Kochan R., Kowalski M.: Safety Management of Textile Products in the European Union and Estimation of its Efficiency. Part 2. General problems of the fibre and textile industries, Fibres & Textiles in Eastern Europe, 2020, 28, 3(141), pp. 12-17. https://doi/org/10.5604/01.3001.0013.9012
2. Global fashion industry statistics – International apparel Available from: https://fashionunited.com/global-fashion-industry- statistics/, Accessed: 2023-08-30
3. Shcherban V., Paraska G., Orlovskyi B., et al.: Resource-saving technologies and equipment of the sewing and textile industry. T. 2: Ways to improve the efficiency of the sewing and textile industries of Ukraine based on the advanced technologies and management: Monograph, Kyiv, KNUTD, 2015, pp. 260. [in Ukrainian]
4. Mittal K., Bahners T.: Textile Finishing: Recent Developments and Future Trends, John Wiley&Sons, 2017, pp. 588.
5. Ilic S., Petrovic T., Djukic G.: Eco-innovation and Sustainable Development, Problems of sustainable development, 2022, 17(2), pp. 197-203. http://doi.org/10.35784/pe.2022.2.21
6. Laitala K., Klepp I., Kettlewell R., et al.: Laundry Care Regimes: Do the Practices of Keeping Clothes Clean Have Different Environmental Impacts Based on the Fibre Content? Sustainability, 2020, 12(18), pp.7537. https://doi.org/10.3390/su12187537
7. Louis Tan Tai Ho.: Formulating Detergents and Personal Care Products: A Complete Guide to Product Development, 2000, US: American Oil Chemists' Society, pp. 465.
8. Laundry Experience Event 2017. March 17-18th, 2017, Helmond, Netherlands. Available from: https://www.cinet-online.com/laundry-experience-event-2017/, Accessed: 2023-07-20
9. Paraska O., Kovtun H., Hes L., et al.: Study of the influence of antimicrobial agents on the operational and hygienic properties of cellulose materials, Vlakna a textil Journal, 2022, 29(2). pp. 73-78. http://dx.doi.org/10.15240/tul/008/2022-2-008
10. Troynikov O., Watson C., Jadhav A., et al.: Towards sustainable and safe apparel cleaning methods: A review, Journal of Environmental Management, 2016, 182(1), pp. 252-264. https://doi.org/10.1016/j.jenvman.2016.07.078
11. Patent for inventions 133667 Composition for laundring household textile products [in Ukrainian]
12. Patent for inventions 133668 Composition of environmentally safe substances for wet cleaning of textile products [in Ukrainian]
13. Belkacem Said-Houari.: Differential Equations: Methods and Applications, 2016, Springer Cham, pp. 212. https://doi.org/10.1007/978-3-319-25735-8
14. Ivasyshen S., Lavrenchuk V., Nastasiyev P., et al.: Differential equations: methods and applications, 2010, Chernivtsi: Chernivtsi National University, pp. 288. [in Ukrainian]

15. Paraska O., Sioma A., Karvan S.: Vision methods of examining the cleanliness of textile materials, Mechanics and control, 2012, 31(1), pp. 44-50. http://dx.doi.org/10.7494/mech.2012.31.1.44
16. DSTU 4143-2002/GOST 31101-2003. Textiles. Evaluation of the wrinkle recovery of fabrics.
17. DSTU GOST 3816:2009 (ISO 811-81). Textile fabrics. Methods for determination of hygroscoric and water-repellent properties.
18. Secondary Materials and Recycled Textiles (SMART) Association. Available from: https://www.smartasn.org/, Accessed: 2023-07-20
19. CINET. Available from: https://www.cinet- online.com/, Accessed: 2023-08-30
20. Paraska O., Ivanishena T.: Methodological bases of life cycle assessment of textile products cleaning technologies at the cleaning industry enterprises, Book of extended abstracts International scientific conference accounting, audit, analysis: Transformation of science and business in new economic reality, Vilnius, Lithuania, 25-26 November, 2021, Vilnius University Press, Vilnius, pp. 75-79. https://doi.org/10.15388/Transformation-of-science-and-business.2021