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SPINNING DISC TECHNOLOGY FOR TEXTILE WASTEWATER TREATMENT: CHARACTERISTICS, MODELING/OPTIMIZATION STUDY

BY

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Abstract. The spinning disc (SD) technology has been used for a number of applications due to its improved attributes. This study focuses on applying SD technology to a textile wastewater treatment in order to improve, without any other additional treatment, its suspended solids and color contents. An experimental planning based on a central compositional rotatable matrix of 2^3 order is used for modeling. Also, the optimal values of all considered process variables (independent ones: flow rate (z_1) within 10-30 L/h experimental range, disc rotational speed (z_2) in 200-1100 rpm range, operating time (z_3) within 5-30 min range) were established together with the dependent ones: treatment degree of suspended solids content (Y_1) and discoloration (Y_2). The SD treatment feasibility was reasonably good (max. $Y_1 = 45.07\%$ and $Y_2 = 26.59\%$). Thus, it can minimize color and solids loads within a relatively short time period and can be used within the primary treatment step.

Keywords: discoloration, flow rate, spinning disc (SD) technology modeling and optimization, suspended solids removal, textile wastewater treatment.

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1. Introduction

The spinning disc (SD) technology has been used in the last years in a number of new applications due to its enhanced fluid flow characteristics, *i.e.* vortices and surface ripples and thus, improved transport phenomena. Intense mixing capability, short residence times, plug flow, low propensity to foul, possibility for particle size and shape control, suitability for ‘fast’ reactions (*e.g.* hydrogenations; polymerizations, etc.), or for other set-up alterations (*e.g.* UV radiation), make the SD technology one of the resourceful techniques that can be applied in a wide range of industry fields, such as cosmetics and pharmaceutics production (Khan and Rathod, 2014; Sana *et al*., 2019), biodiesel synthesis (Qiu *et al*., 2012) or enzymatic reactions (Feng *et al*., 2013).

The textile wastewaters (WWs) are considered to be a potential pollution source of persistent organic pollutants (POPs) and also suspended solids (SS) which might pose a risk to humans and the environment if they are not eliminated correspondingly by using efficient WW treatment technologies (Anirudhan and Ramachandran, 2015; Aziz *et al*., 2015; Bilińska *et al*., 2017; Giuliano *et al*., 2017; Iacob Tudose and Zaharia, 2020; Rodrigues *et al*., 2017; Tawfik *et al*., 2017) such as mixed processes and operations like coagulation-flocculation, advanced oxidation (with/without catalysts and/or UV-Vis irradiation, sonolysis), adsorption, biological oxidation, membrane (Chen *et al*., 2019; Meng *et al*., 2020; Mo *et al*., 2018; Zhang *et al*., 2019) or electrochemical processes in association with solids separation by settling, sand filtration or multi-bed filtration, among others. Alternatives to these processes are known as adaptable to specific critical situations and new ones are tested as innovative WW treatment solutions, especially for relatively small mono- block area of industrial WW treatment station. This research work proposes the discussion of such an industrial WW treatment, namely the spinning disc technology applied in the case of real textile WWs treatment systems. After the dyeing process of different textile products (fabrics, carpet, yarn, fibers), many textile dyes (non-fixed on textile fibers or other manufactured materials, meaning more than 10 - 20% from the total dyes amount used) are released into the WW and can be visually identified by WW color, and also, its suspended solids (in form of dispersed dyes, metal complex azo dyes, pigments or other composite agglomerates formed in the WW treatment process) (Ahn *et al*., 1999; Aziz *et al*., 2015; Zaharia *et al*., 2012). The discharge of non-treated textile WWs in aquatic receptors is undesirable due to the toxicity of many residuals and their breakdown products towards different living forms (daphnia, fishes, algae, plants, bacteria).

Reliable wastewater treatment is necessary in the textile industry, therefore efficient modeling and treatment control methods are becoming very important in each treatment process proficiency. Thus, data accumulation and very good fundamental and practical understanding of the WW treatment processes are required, which imposes the necessity of mathematical modeling and even simulation (Ataei *et al*., 2011; Zaharia, 2015).

The key operating parameters (independent variables) influencing the removal efficiency (as dependent variables) must be well selected, also, the prediction model efficiency and the analysis sensitivity should be improved. However, usually it is difficult to predict results considering simultaneously a very high number of variables (more than 10 variables), that is why good experimental results are seldom obtained by consideration of no more than 3-5 variables (Behbahani *et al*., 2013; Domínguez *et al*., 2016; Iboukhoulef *et al*., 2018; Pajootan *et al*., 2016; Srivastava *et al*., 2017; Xiang *et al*., 2015; Yoo *et al*., 2001).

This study focuses on applying SD technology to a real textile wastewater treatment in order to improve its characteristics, especially those referring to the content of suspended solids and color, without any other additional treatment (*i.e*. advanced oxidative, or reductive, or biochemical processes). Also, an experimental planning based on a central composite rotatable 2^3 order design, used to model the studied textile WW treatment within the SD setup, is proposed. Three independent variables (WW flow rate, disc rotational speed and contact time), in association with the discoloration degree (%) and suspended solids removal (%) as optimization criteria (decision functions) are studied and their optimal values are found. This paper continues the authors research work in textile WW treatment control, modeling and optimization, based on a single-step treatment, the mechanical one. This work aims to continue the research initiated by the authors in the field of industrial WW purification control, applied in a single mechanical step, and also, in process modeling and optimization.

Thus, the SD technology feasibility, applied in the textile WW treatment related to the reduction and control of color and suspended solids loads, within a relatively short time, without the use of any additional mechanical, chemical or other type of treatment, is evaluated. This technology can be an alternative to the classical mechanical step, applied within the primary and/or secondary WW treatment step.

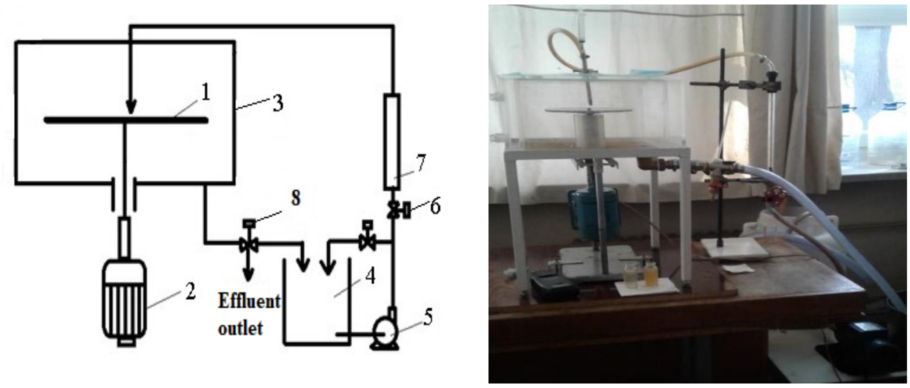
2. Experimental part

2.1. SD setup

Spinning disc technology (SD) involves the use of centrifugal force created by the rotation of a disc surface on which a liquid is fed, and the formation on its surface of a thin liquid film that travels predominantly radially to the edge of the disc.

The real textile wastewater was fed on a rotating smoothed-surface disc, of 20 cm diameter, in a laboratory experimental setup (Fig. 1).

The disc 1 was connected to a variable adjustable speed motor 2 and was enclosed in an acrylic housing 3. The textile wastewater was treated with bentonite (2 g/L) in tank 4 to facilitate subsequent solids agglomeration and discoloration, and afterwards, it was fed onto the disc, using a pump 5. The wastewater flow rate was maintained constant using tap 6 and measured with the flowmeter 7. The disc rotational speed was established with a laser tachometer, with a ± 0.1 rpm accuracy. The wastewater outlet effluent, used for quality measurements, was collected from tap 8.



(a) (b)

Fig. 1 – Spinning disc experimental setup: (a) schematic representation of SD setup, (b) image of laboratory spinning disc (SD) equipment (1-spinning disc; 2-motor; 3-case; 4-WW storage tank; 5-pump; 6-flow control valve; 7-flow meter; 8-exit tap for sample collection).

The WW temperature was measured using a calibrated thermometer and was found to have a constant value of approximately 20°C (± 0.1°C).

Some of the investigated operating variables thought to influence the hydrodynamics on the disc and consequently, the wastewater characteristics, were the liquid supplying flow rates (within 10 to 30 L/h) and the disc rotational speeds (within 200 to 1100 rpm).

The SD treatment efficiency applied on the studied textile WW was expressed as a percentage of suspended solids and color removals (Yi, %), calculated with Eq. (1) (Zaharia *et al.*, 2012).

$$Yi\,[\%] = [(C_o - C_t)\,/\,C_o] \cdot 100 \qquad (1)$$

where: C_0 and C_t are the initial and final suspended solids content or colour of treated WW sample after t time (min) of SD treatment, (mg/L) or (HU).

2.2. Analytical analysing, modeling and optimization methodology

2.2.1. Analytical analysis methods

PH determination. The pH measurement was achieved with the Hanna high precision KL-009(I) pH-meter (Hanna Instruments Co.).

Colour determination. The colour was expressed byas the Hazen colour index (*i.e.* 50 Hazen units (HU) are equivalent to an absorbance value of 0.069 at 456 nm with respect to distilled water as blank) or directly, as absorbance value, at three different characteristic wavelengths, *i.e.* 436, 525 and 620 nm (especially, 436 nm for industrial wastewaters, according to the SR ISO 7887/97 standard) (Catalog, 2015; Zaharia, 2015; Zaharia *et al*., 2012). The absorbance measurements were performed with DR/2000 Direct Reading Spectrophotometer (Hach International Instruments Co.).

Suspended solids content determination. It was performed by direct reading at the DR/2000 Direct Reading Spectrophotometer (Hach, International Instruments Co.) using the test program no. 630 (in mg/L) for the WW suspended solids content with respect to a distilled water blank.

All other characteristics of the studied textile WW have been analysed by means of the corresponding recognized standard analysis methodology, internationally approved (Catalogue, 2015), and/or presented in other authors reports (Zaharia, 2015; Zaharia *et al*., 2012) by using standard kits and specific reference reagents, adapted for DR/2000 spectrophotometer.

2.2.2. Modeling and optimization methodology

All performed experimental measurements were used to model and afterwards, optimize the SD treatment process.

The central composite rotatable planning (2^3 order design) of the SD experimental data was used, considering as main independent variables: the wastewater flow rate (z_1), the disc rotational speed (z_2), the operating time (z_3), and as dependent treatment variables (or optimization criteria) the WW treatment degrees for suspended solids content (Y_1, %) and textile WW discoloration (Y_2, %).

A mathematical model was proposed for each optimization criterion (expressed by coded value x_i of each dependent variable z_i, i = 1-3) (Eq. (2)), the model coefficients significance being investigated using the Student test. Also, the experimental data deviation from their mean calculated value was established, and it was checked if this deviation is either due to the experimental errors, or significant influence of studied independent variables (deviation must be in range of –10% and +10% for a very good accordance).

$$Y_i=a_0+\sum a_i.x_i+\sum a_{ii}x_i^2+\sum a_{ij}x_ix_j \qquad (2)$$

where: Y_i represents the optimisation criterion or decision function (dependent variable); x_i, x_j, x_{ii}, x_{ij} are the coded variables of the SD treatment system, and a_0, a_i, a_j, a_{ij} are the model coefficients (i, j = 1, 2, 3).

The least square fitting method applied to the data obtained in the design points (20 experimental points) was used to calculate the model coefficients. The main advantage of central active composite rotatable design consists of no excessive experiments referring to the coefficients number, *i.e.* 20 experiments, namely: N^F factorial experiments (2^3=8) performed at the corner of the cube corresponding to the experimental data area; N_a axial experiments (2×3=6) performed on the axes at a distance of $\pm\alpha_i$ from the centre, calculated such as to attain rotability ($\alpha_i = \pm 1.682$ for a central active composite rotatable 2^3 design); N_0 central experiments (N_0 = 6) in the centre of the experiment field (for estimation of 'pure' experimental error or reproducibility variance) (Cojocaru *et al.*, 2010; Domínguez *et al.*, 2016; Macoveanu and Nicu, 1987; Rodrigues and Iemma, 2014; Srivastava *et al.*, 2017; Xiang *et al.*, 2015; Zaharia, 2015). The x_i coded value of real z_i variable was calculated with Eq. (3) (Curievici, 1980; Domínguez *et al.*, 2016; Rodrigues and Iemma, 2014; Zaharia, 2015):

$$x_i = (z_i - z_{i0}) / \Delta z_{i0} \tag{3}$$

where z_i represents the independent variable, z_{i0} is its basic value and Δz_{i0}, its variation step.

Afterwards, the Fisher constant (F), the multiple correlation coefficient (R_{Yi}) were calculated and also, the Fisher test (F_c) was applied to establish if the tested independent variables had a significant influence related to each optimization criterion, all the used formulae being included in Table 1.

Table 1

Fisher constant (F), multiple correlation coefficient (R_{Yi}), and Fisher test (F_c) formulae

Correlation tests	Formulae	Coefficient name
Fisher constant (F)	$F = \dfrac{(n-1)\cdot\sum_{i=1}^{n}(Y_{ei} - \overline{Y_e})}{(k-1)\cdot\sum_{i=1}^{k}(Y_{ek1} - \overline{Y_{ek}})}$	Y_{ei} – experimental results; $\overline{Y_e}$ – mean value of experimental results; Y_{eki} – experimental results in center of experimental design planning; $\overline{Y_{ek}}$ – mean value of experimental results in center of design planning; Y_{ci} – proposed model calculated results; n – experiments number; k – number of central experiments; b – number of independent variables.
Multiple correlation coefficient (R_{Yi})	$R_{Y_i} = \sqrt{1 - \dfrac{\sum_{i=1}^{n}(Y_{ei} - Y_{ci})^2}{\sum_{i=1}^{n}(Y_{ei} - \overline{Y_e})^2}}$	
Fisher test (F_c)	$F_C = \dfrac{n-b-1}{b}\cdot\dfrac{R^2_{Yx1x2x3}}{1-R^2_{Yx1x2x3}}$	

All optimal values of the model variables were established after applying a classical optimization procedure.

3. Results and discussion

3.1. Textile wastewater characteristics

In this experimental study, a real textile wastewater obtained from the manufacturing of cotton fabrics (a textile wastewater resulted after the 2nd and 3rd rinsing steps of finishing process) (Zaharia, 2015) was treated in the SD setup. The WW can contain a few residuals such as azo dyes (Remazol Arancio 3R, Remazol Rose RB), tensides, NaOH, Na_2CO_3, specific auxiliaries, among others (Zaharia, 2015; Zaharia *et al.*, 2012) and had significantly exceeded the maximum admissible concentrations for some quality indicators (*i.e.* color, COD, BOD_5, total dissolved solids, suspended solids, salts, fixed residues, total phosphorus, etc.). Before final discharge or inside reuse, its treatment is necessary at least as a primary treatment step, developed as simple as possible (ideally in one single-stage treatment), a feasible alternative being the SD technology.

The main quality indicators of studied real textile WW are presented in Table 2 (Zaharia, 2015).

Table 2

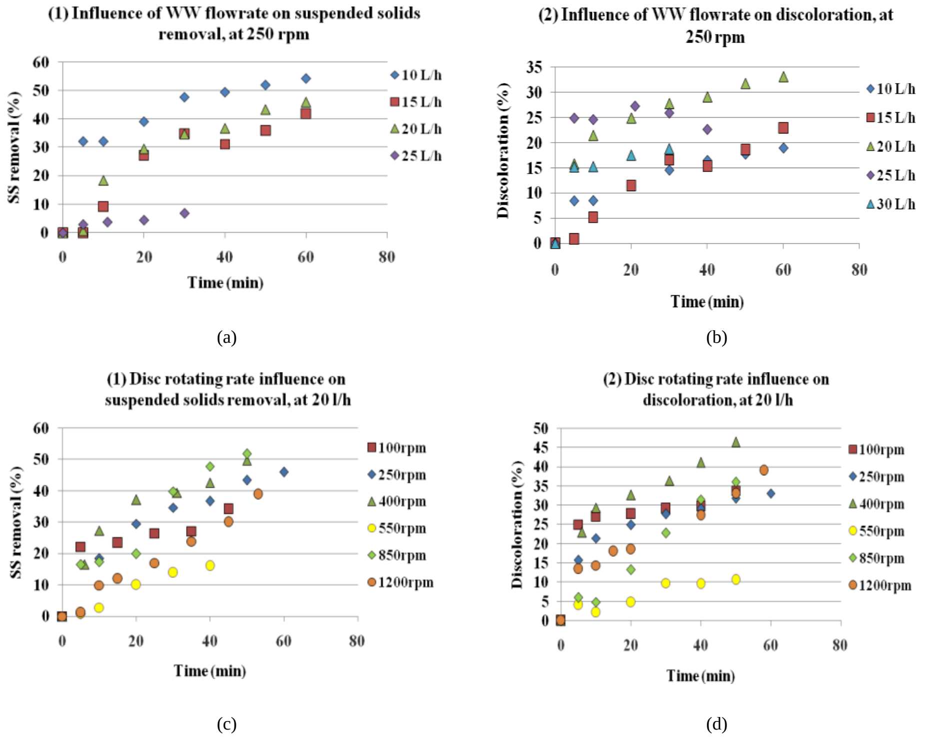
The principal quality indicators of studied real textile effluents

Quality indicators	Measured value (mg/L)	M.A.C.* (mg/L)	Quality indicators	Measured value (mg/L)	M.A.C.* (mg/L)
pH	7.12-7.89	6.50-8.50	Total P	5.70-10.45	1
Colour, [HU] (A_{436})	865-4445 (1.200-2.620)	50	Extractible substances	25.50-31.80	20
Suspended solids	382-930	35 (60)	Total N	8.30-10.00	10
Turbidity, [FTU]	180-815	-	Ammonia	2.0-2.75	2
Fixed residues	3580-4050	1000	Sulphates	780-850	600
COD, [mg O_2/L]	560-660	125	Chlorides	95-150	70
BOD_5, [mg O_2/L]	330	25	Phenol index	2.60-3.50	0.30
Synthetic detergents	1.70-2.50	0.50	Total heavy metal ions	< 4	< 2 (max 5)

*M.A.C. – maximum acceptable concentration, according to Romanian standard, Decision No. 352/2005-Technical Norms for Treated Wastewater Discharged in Natural Water Resources (NTPA 001).

3.2. Influence of studied independent variables onto the textile wastewater treatment degree

Some variation characteristics of the studied independent variables (WW flow rate, disc rotational speed and contact time) in their studied experimental field are illustrated in Fig. 2 considering a few reference treatment working conditions of the SD setup. Temperature variation during one experimental test was no more than ±0.05°C.


(1) Influence of WW flowrate on suspended solids removal, at 250 rpm

(2) Influence of WW flowrate on discoloration, at 250 rpm

(a) (b)

(1) Disc rotating rate influence on suspended solids removal, at 20 l/h

(2) Disc rotating rate influence on discoloration, at 20 l/h

(c) (d)

(b) *Disc rotational speed influence at 20 L/h on suspended solids removal* ***(1)*** *and WW discoloration* ***(2)***

Fig. 2 − Influence of textile WW flow rate at 250 rpm on suspended solids removal (a) and WW discoloration (b) and disc rotational speed on SD setup efficiency (1 h) at 20 L/h on suspended solids removal (c) and WW discoloration (d).

Experimental data suggested that one can select a certain flow rate and rotational speed domain in the SD setup to be used in the textile wastewater treatment, depending on the needed flow characteristics, either plug or stirred flow.

For a disc rotating rate of 250 rpm, suspended solids removals higher than 40% were obtained when the SD treatment was applied, for WW flow rates in the range of 10 - 20 L/h (with a maximum of 54.29% at 60 min, at 10 L/h) and discoloration degrees higher than 20% (but no more than 35%) for WW flow rates in the range of 15 - 25 L/h (a maximum of 33.16% at 50 min, at 20 L/h). For a WW flow rate of 20 L/h, suspended solids removals higher than 40% were performed for 850 rpm, 400 rpm and 250 rpm (with a maximum of 51.88% at 50 min and 850 rpm) and discoloration degrees higher than 30%, for the disc rotational speeds of 400 rpm, 850 rpm, 1200 rpm and 250 rpm (with a maximum value of 46.49% at 50 min and 400 rpm).

One can notice that the parameter values that render maximum suspended solids removal and discoloration are not similar since the mechanisms involved are different. Also, an increase in liquid flow rate slightly enhances micromixing, however the disc rotational speed has a higher impact on developing convective microstructures that improve the mass transfer or other processes such as adsorption. At the same time, an increase in liquid flow rate and disc rotational speed determine a decrease in the liquid residence times on the disc, which basically reduces the benefit of intense micromixing. Thus, the interplay between the micromixing within the liquid film and the liquid residence time on the disc, may render different liquid flow rate and disc rotational speed values for the maximum suspended solids or color removals, depending on the mechanisms involved.

In the primary WW treatment step, a few unitary operations, such as sedimentation and filtration, can be used, to obtain treatment efficiencies of 40-60% for suspended solids removal and 25-35% for WW discoloration. The experimental results, shown in Fig. 2, lie within similar interval values and thus, indicate the possibility of SD setup use in the primary step of the textile WW treatment. For a good control of the SD setup use in a specific WW treatment, the treatment modeling and optimization are necessary.

3.3. WW treatment modeling by using the SD technology

This work proposes a preliminary modeling and optimization study for estimation of the SD technology feasibility in the case of studied textile WW treatment, with the main target of WW discoloration and suspended solids removal, for possible reuse or discharge into a nearby natural aquatic receptor.

The real and coded values for the three investigated independent variables of the SD setup for the textile WW treatment application are presented in Table 3, together with their variation steps.

Table 3

Encoding of the independent variables in the central active composite rotatable 2^3 design

Independent variable/ value	*Real variable (z_i)*	*Coded variable (X_i)*	*Real basic variable (z_{i0})*	*Variation step (Δz_{i0})*
Flow rate, (L/h)	z_1	x_1	20	5
Disc rotational speed, (rpm)	z_2	x_2	500	300
Contact time, (min)	z_3	x_3	15	5

The obtained experimental results allowed the proposal of the mathematical models, individually for each Y_i dependent variable, but also the finding of the optimal values for all independent variables, for maximum values of both dependent variables (optimization criteria).

Table 4 shows the experimental planning matrix of central active composite rotatable 2^3 order design, which illustrates the correlation between experimental and model-based calculated data.

Table 4

Central active composite rotatable 2^3 order design experimental planning matrix

Exp. No.	z_1 (L/h)	z_2 (rpm)	z_3 (min)	x_1	x_2	x_3	Y_{1e} (%)	Y_{1c} (%)	*Deviation* Y_1	Y_{2e} (%)	Y_{2c} (%)	*Deviation* Y_2
1	15	200	10	-1	-1	-1	45.065	37.439	+0.1690	26.587	24.098	+0.0936
2	25	200	10	1	-1	-1	36.22	30.738	+0.1513	24.012	20.656	+0.1398
3	15	800	10	-1	1	-1	34.59	33.356	+0.0357	17.058	17.109	-0.0030
4	25	800	10	1	1	-1	30.168	30.543	-0.0124	20.566	21.535	-0.0471
5	15	200	20	-1	-1	1	44.507	37.439	+0.1588	25.753	22.878	+0.1116
6	25	200	20	1	-1	1	35.102	30.738	+0.1243	17.301	15.344	+0.1131
7	15	800	20	-1	1	1	35.475	33.356	+0.0597	18.462	19.474	-0.0548
8	25	800	1520	1	1	1	29.423	30.543	-0.0381	18.789	19.372	-0.0310
9	11.59	500	15	-1.682	0	0	29.05	38.068	-0.3104	19.985	23.086	-0.1552
10	30.09	500	15	1.682	0	0	26.816	30.067	-0.1212	17.954	20.473	-0.1403
11	20	100	15	0	-1.682	0	34.358	35.494	-0.0331	20.493	21.542	-0.0512
12	20	1004.6	15	0	1.682	0	34.358	32.124	+0.0650	19.804	18.159	+0.0831
13	20	500	6.59	0	0	-1.682	27.374	31.101	-0.1362	19.732	20.437	-0.0357
14	20	500	23.41	0	0	1.682	36.778	32.012	+0.1296	21.110	18.680	+0.1151
15	20	500	15	0	0	0	33.333	34.068	-0.0220	19.042	21.779	-0.1437
16	20	500	15	0	0	0	31.192	34.068	-0.0922	20.276	21.779	-0.0741
17	20	500	15	0	0	0	29.795	34.068	-0.1434	20.820	21.779	-0.0461
18	20	500	15	0	0	0	31.006	34.068	-0.0988	20.530	21.779	-0.0608
19	20	500	15	0	0	0	32.868	34.068	-0.0365	20.384	21.779	-0.0684
20	20	500	15	0	0	0	29.516	34.068	-0.1542	19.478	21.779	-0.1181
Mean value:							*33.350*	*33.371*	*-0.3048*	*20.407*	*20.676*	*-0.0356*

The proposed model for SD treatment setup is presented below considering all significant coefficients (Eqs. (4) – (5)) after the Student test application (t) described in Table 5.

The calculation of model coefficients was performed with the specific mathematical formulae, well-known in statistics and described in-detail in previous research reports (Cojocaru *et al.*, 2010; Popescu *et al.*, 2010; Zaharia and Suteu, 2014; Zaharia, 2015).

$$Y_1 = 34.0677 - 2.3784x_1 - 1.0697x_2 - 1.0486x_3^2 + 0.972x_1x_2 \tag{4}$$

$$Y_2 = 21.7791 - 0.7768x_1 - 0.7404x_2 - 0.8459x_3 - 0.6899x_2^2 - 0.9772x_3^2 + 1.8578x_1x_2 - 1.1323x_1x_3 + 0.8965x_2x_3 \tag{5}$$

Table 5

Student test results for the proposed models (Y_1 and Y_2)

Y_1						Y_2					
Model coefficient	Coefficient value	Dispersion	t	$t_{critical}$	Sign	Model coefficient	Coefficient value	Dispersion	t	$t_{critical}$	Sign
a_0	34.0677	0.34837	97.7916	2.571	+	a_0	+21.7791	0.152327	142.9759	2.571	+
a_1	-2.3784		-6.8273		+	a_1	-0.7768		-5.0994		+
a_2	-1.0697		-3.0706		+	a_2	-0.7404		-4.8605		+
a_3	+0.2863		+0.8219		-	a_3	-0.8459		-5.5537		+
a_{11}	-0.5159		-1.4809		-	a_{11}	-0.3438		-2.2570		-
a_{22}	+0.5110		+1.4669		-	a_{22}	-0.6899		-4.5290		+
a_{33}	-1.0486		-3.0099		+	a_{33}	-0.9772		-6.4150		+
a_{12}	+0.9720		+2.7901		+	a_{12}	+1.8578		+12.1958		+
a_{13}	-0.2738		-0.7858		-	a_{13}	-1.1323		-7.4330		+
a_{23}	+0.2270		+0.6516		-	a_{23}	+0.8965		+5.8854		+

The deviation of the experimental data related to the mean value was of around -0.31% for Y_1 and -0.036% for Y_2, within acceptable limit (< ± 10%). The validation of the proposed models was carried out by an appropriate analysis of Fisher constant (F) variance. The calculated values were found to be $F_1 = 141.85$ for Y_1 and $F_2 = 192.43$ for Y_2, higher than the statistical reference value F_{tab}=4.6 (for $\alpha = 99$, $\nu_1 = n - 1 = 19$, $\nu_2 = k - 1 = 2$, where n is the number of experiments, and k is the number of independent variable), underlining the significant influence of the independent variables on the optimization criterion (dependent variable, Y_1 and Y_2). But the calculated multiple correlation coefficients were relatively low, *i.e.* $R_{Y1} = 0.54$ for Y_1 and $R_{Y2} = 0.60$ for Y_2, due to the fact that the investigated experimental fields of flow rate (11.59 - 30.09 L / h) and rotating rate (100 - 1045 rpm) were quite large. Our subsequent tests, performed for lower (restrictive) experimental variation fields of the rotating rate (100 - 550 rpm) and feeding liquid flowrate (9.908 - 30.09 L / h), rendered correlation coefficient values both higher than 0.808, indicating a better correlation between the experimental and the modeled data (Zaharia and Iacob-Tudose, 2019). Therefore, the significant influence of the independent variables on each optimization criterion is sustained.

The calculated values of Fisher test were of $F_{c,1}$ = 20.09 for Y_1 and $F_{c,2}$ = 8.84 for Y_2, and related to the reference statistical value F_{tab} = 6.59 (for freedom degrees of ν_1 = n - k-1 = 16 and ν_2 = k = 3), one can conclude that the evaluated independent variables had a substantial impact on the removal of suspended particles and colour from textile wastewater.

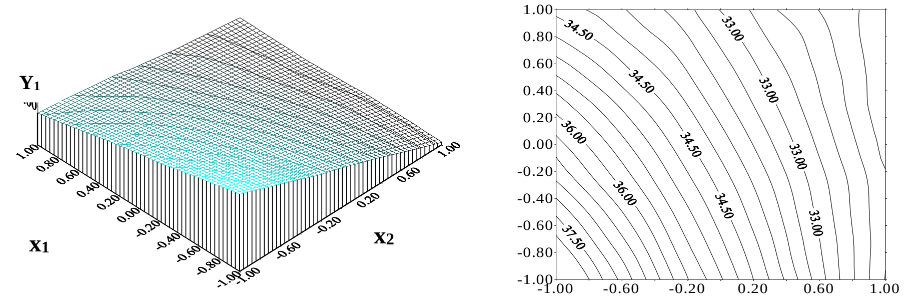
3.4. Analysis of the proposed mathematical models

The decision function (Y_i) analysis leads to the conclusion that all three independent variables x_i (the WW flow rate, the disc rotational speed and the operating time) have an important influence on the suspended solids removal (Y_1) from the studied textile WW, fact demonstrated by the values of the x_1, x_2 and x_3 coefficients much higher than unity. The influence of the WW flow rate (x_1 variable) is almost 2.223 times higher than that of the disc rotational speed (x_2), and 2.268 than the influence of the operating time (x_3) for suspended solids removal (Y_1). These parameters influences are not opposite, which is indicated by the positive x_1x_2 coefficient value. For colour removal (Y_2), all independent variables had a similar impact, however smaller than those for suspended solids removal (x_i coefficient < 1). Also, their influences on WW discoloration are not opposite in the case of flow rate and rotating rate (x_1x_2), or rotational speed and contact time (x_2x_3), but divergent in the case of flow rate and contact time (x_1x_3).

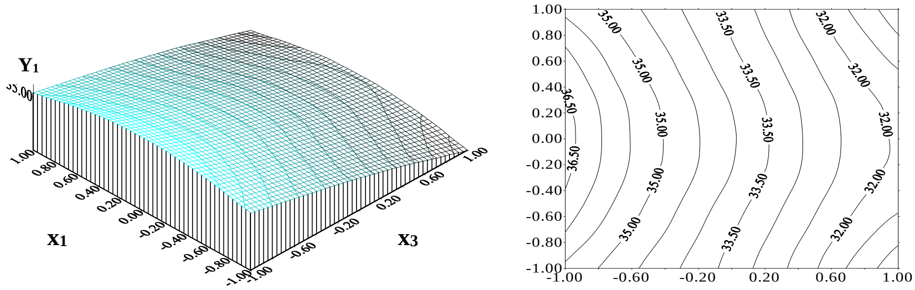
The application of classical optimization method leads to the conclusion that the maximum efficiency of SD technology applied as a single textile WW treatment without any other type of process/operation involved is reasonably good and locally available at 15 L / h flow rate, 200 rpm disc rotational speed, and a treatment time of 10 or 20 min (45.07% or 44.51% for SS removal, and 26.59% or 25.75% for colour removal), but the optimal efficiency of SD technology is performed by working at 12 L / h flowrate, 500 rpm disc rotational speed and 15 min of WW treatment for suspended solids removal (38.068%), or at 23.5 L / h flowrate, 705 rpm rotational speed and 17.2 min of textile WW treatment for colour removal (20.66%).

For optimal removal of both dependent variables (Y_1 and Y_2) (meaning maximum of the both dependent variables sum, $Y = \Sigma Y_i \rightarrow$ Maximum), the values of studied independent variables must be of: x_1^*= -0.2739, x_2^*= -0.9779, x_3^* = - 0.3486, which are translated in real values to 18.63 L / h, 206.63 rpm and 13.26 min, corresponding to Y_1^* = 44.1035% for suspended solids removal and Y_2^* = 28.349% for WW discoloration.

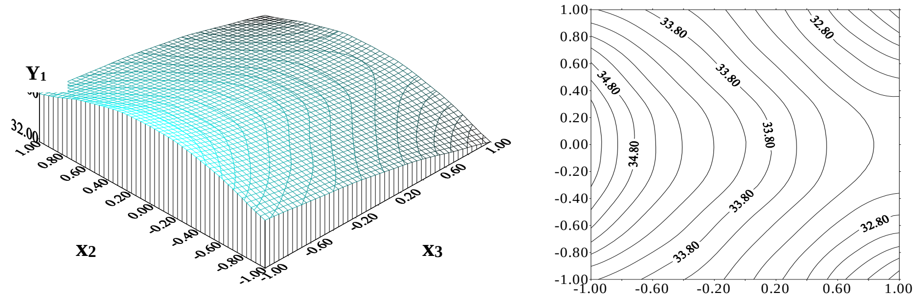
Figures 3 (a - c) and 4 (a - c) illustrate the dependence of the suspended solids removal (Y_1) and WW discoloration (Y_2) versus two independent variables (one variable was kept at the basic value) (*i.e.* $Y_i = Y_i\,(x_1,x_2,0)$, $Y_i = Y_i(x_1,0,x_3)$ and $Y_i = Y_i(0,x_2,x_3)$).



***(a)** three-dimensional Y_1=Y_1(X_1,X_2,0) and its isolines*

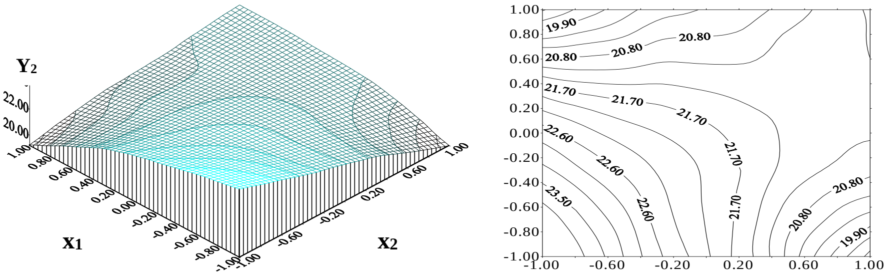


***(b)** three-dimensional Y_1=Y_1(X_1,0,X_3) and its isolines*

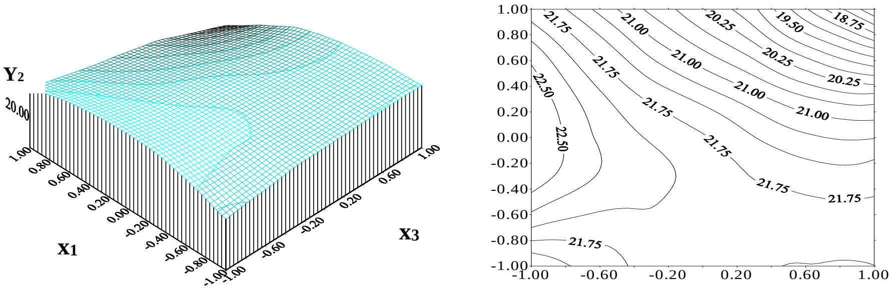


***(c)** three-dimensional Y_1=Y_1(0,X_2,X_3) and its isolines*

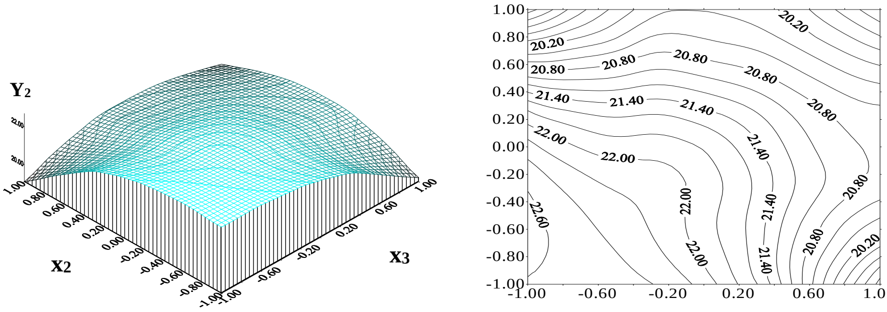
Fig. 3 − Suspended solids removal variation ($Y1$) with two independent variables (one variable held constant);
(a) $Y_1 = Y_1(X_1, X_2, 0)$; (b) $Y_1 = Y_1(X_1, 0, X_3)$; (c) $Y_1 = Y_1(0, X_2, X_3)$.



(a) three-dimensional $Y_2=Y_2(X_1,X_2,0)$ and its isolines



(b) three-dimensional $Y_2=Y_2(X_1,0,X_3)$ and its isolines



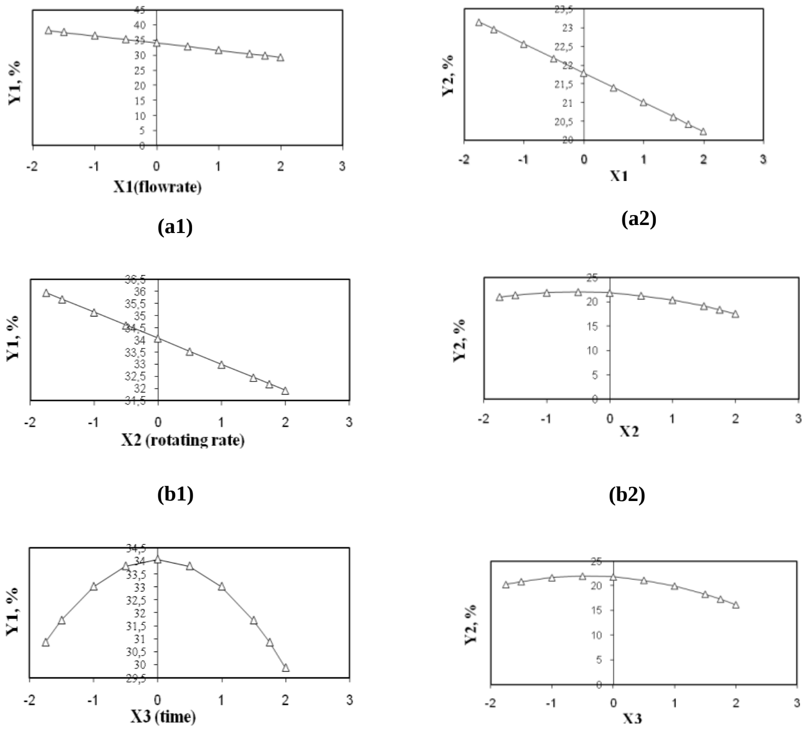
(c) three-dimensional $Y_2=Y_2(0,X_2,X_3)$ and its isolines

Fig. 4 − Variation of WW discoloration (Y_2) vs. two independent variables (one variable kept constant). (a) $Y_2 = Y_2(X_1, X_2, 0)$; (b) $Y_2 = Y_2(X_1, 0, X_3)$; (c) $Y_2 = Y_2(0, X_2, X_3)$

The decrease of suspended solids removal (Y_1) and discoloration (Y_2) with the increase of WW flow rate (x_1) is highlighted in Figs. 5(a1) and 5(a2). It seems that a *local maximum* exists (for both decision functions, $Y_1^* = 38.23\%$ and $Y_2^* = 23.14\%$) corresponding to a WW flow rate of 11.25 L / h ($x_1^* = -1.75$), a rotational speed of 500 rpm ($x_2^* = 0$) and a working time interval of 5 min ($x_3^* = 0$).

The decrease of suspended solids removal (Y_1) and the increase of WW discoloration (Y_2) with the increase of rotational speed (x_2) is illustrated in Figs. 5(b1) and 5(b2). It seems that exists a *local maximum* of *suspended solids removal* (Y_1^*=35.94%) corresponding to a WW flow rate of 20 L / h (x_1^*=0), a rotational speed of 25 rpm (x_2* = - 1.75) and a working time period of 5 min (x_3* = 0), and a *maximum* of *WW discoloration* (Y_2* = 21.98%) corresponding to a WW flow rate of 20 L / h (x_1* = 0), a disc rotational speed of 350 rpm (x_2* = - 0.5) and a working time period of 5 min (x_3* = 0).

The variation of suspended solids removal (Y_1) and WW discoloration (Y_2) with the working time (x_3) is shown in Figs. 5(c1) and 5(c2). It seems that a *maximum* of *suspended solids removal* exists (Y_1^* = 34.07%) corresponding to a WW flow rate of 20 L / h (x_1* = 0), a rotational speed of 500 rpm (x_2* = 0) and a working time period of 15 min (x_3* = 0), and a *maximum* of *WW discoloration* (Y_2* = 21.23%) corresponding to a WW flow rate of 20 L/h (x_1* = 0), a rotational speed of 500 rpm (x_2* = 0) and a working time period of 4.18 min (x_3* = - 0.433).



(a1) (a2)

(b1) (b2)

(c1) (c2)

Fig. 5 − The dependence of Y_i (Y_1 and Y_2) on each independent variable x_i.
(a_i) $Y_i = Y_i(x_1, 0, 0)$; (b_i) $Y_i = Y_i(0, x_2, 0)$; (c_i) $Y_i = Y_i(0, 0, x_3)$.

The graphical representations (Figs. 3 - 5) allow to observe each variable characteristic in the experimental field through isolines, and the local maximum for WW suspended solids removal and discoloration efficiency when some of the independent variables are kept constant at their basic values. The WinSurf and Excel data processing programs were used to complete this analysis.

Application of *direct research empirical optimization* methodology, based on univariant search and/or gradient methods (Curievici, 1980; Macoveanu and Nicu, 1987) for the proposed models in this research work, leads to values close to the local maximum obtained by classical optimization methodology (Y_1 = 44.01% and Y_2 = 26.86%), for the following three independent variables values: $X_1* = - 1$, $X_2* = - 1$ and $X_3* = 0$, meaning a WW flow rate of 15 L/h, a rotational speed of 200 rpm and an operating time interval of 15 min.

4. Conclusions

This research work is aimed only to evaluate the SD technology feasibility in the textile WW treatment in association with the empirical modelling of a single mechanical treatment stage, applied to textile WWs, within a SD setup, considering mainly three independent variables (WW flow rate, rotational speed and operating time) and two dependent variables (suspended solids removal and WW discoloration). The optimal values of studied influencing variables were determined by the application of the central active composite rotatable design (2^3 order) and were found to be reasonably good, namely of 44.10% for suspended solids and of 26.59% for colour removals when working with a flow rate of 18.63 L / h, a disc rotational speed of 206 rpm and 13.24 min, or individually, of 45.065% for the highest suspended solids removal and of 28.35% for the highest discoloration degree. Thus, the SD treatment feasibility, especially for suspended solids removal from textile WWs, was preliminarily established (over 44 - 45%) and found to be comparable to that achieved by settling or simple sand filtration. Additional advanced chemical and/or biological processes acting simultaneously in the same mono-block treatment station would increase the removals. Therefore, SD technology can be a potential alternative treatment solution, in the primary WW treatment step, while subsequent advanced innovative treatment steps (oxidative and adsorptive ones) can be beneficially applied for textile WWs safe and environmentally healthy reuse and/or their discharge in natural aquatic surroundings (with an estimated polluting load reduction surpassing 70 – 80%).

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TEHNOLOGIA DISCULUI ROTITOR PENTRU EPURAREA APELOR UZATE TEXTILE: CARACTERISTICI, STUDIU DE MODELARE/OPTIMIZARE

(Rezumat)

Tehnologia discului rotitor (SD) a fost utilizată în ultimii ani pentru o serie de noi aplicații (reacții „rapide” sau alte configurații) datorită caracteristicilor de curgere ale fluidului şi fenomenelor de transport îmbunătățite (de exemplu, timpi de rezidență mici, capacitate intensă de amestecare, posibilitatea de control a dimensiunii şi formei particulelor, printre altele). Acest studiu se concentrează pe aplicarea tehnologiei SD la epurarea apelor uzate textile pentru a îmbunătăți, fără alte tratamente suplimentare (de exemplu, procese oxidative avansate, reductive sau biochimice), caracteristicile acestora, în special cele referitoare la solidele în suspensie şi conținutul de culoare. Astfel, este propusă o planificare experimentală bazată pe o matrice compozițională centrală rotativă de ordin 2^3, utilizată pentru modelarea unei epurări a apelor uzate textile reale. De asemenea, valorile optime ale tuturor variabilelor de proces considerate (adică cele independente: debitul (z_1) într-un interval experimental de 10 - 30 L/h, viteza de rotație a discului (z_2) în intervalul experimental de 200 - 1100 rpm, timpul de operare (z_3) într-un interval experimental de 5 - 30 min) au fost stabilite împreună cu cele dependente: gradul de epurare al conținutului de solide în suspensie (Y_1) și gradul de decolorare a apei uzate textile (Y_2). Fezabilitatea tratamentului SD a fost rezonabil de bună (max. Y_1 = 45,07% și Y_2 = 26,59%) fără utilizarea vreunui tratament suplimentar mecanic, chimic sau de alt tip. Astfel, încărcările de culoare şi solide pot fi minimizate într-o perioadă de timp relativ scurtă dacă se utilizează tehnologia discului rotator care constituie o alternativă adecvată şi eficientă în etapa mecanică clasică aplicată în tratamentul primar al apelor textile uzate.