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The optimization of whiteness of polyester fabric treated with nanoparticles of 2,2′-(vinylenedi-p-phenylene)bis-benzoxazole (OB-1) by the Taguchi method

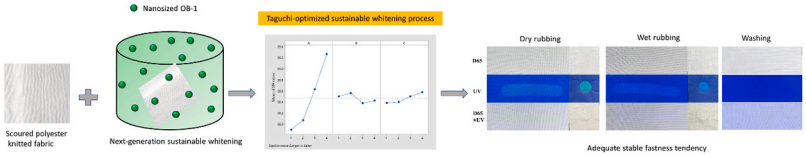
Yingjie Cai [a,b], Le Li [a], Tianjie Wang [a], Ying Ren [a], Md. Nahid Pervez [a], Ai Chen [c], Xiaohua Zhao [c], Lina Lin [a,d,*], Xiaorong Xiong [b,**], Mohammad Mahbubul Hassan [e,**]

[a] Hubei Provincial Engineering Laboratory for Clean Production and High-Value Utilisation of Bio-based Textile Materials, Wuhan Textile University, Wuhan 430200, China
[b] School of Computing, Huanggang Normal University, Huanggang 438000, China
[c] Technical Quality Department, Hubei Hongxin Chemical Co., Ltd, Wuxue 435406, China
[d] Engineering Research Centre for Clean Production of Textile Dyeing and Printing, Ministry of Education, Wuhan Textile University, Wuhan 430200, China
[e] Fashion, Textiles and Technology Institute, University of the Arts London, 20 John Prince's Street, London W1G 0BJ, United Kingdom

HIGHLIGHTS

- A novel method of optical whitening of polyester fabric with nanosized OB-1.
- Taguchi methodology was implemented to optimize the whitening parameters.
- The temperature significantly influences the whiteness of polyester fabric.
- Color fastness properties were adequately stable.

GRAPHICAL ABSTRACT



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ABSTRACT

This study explores a new approach to achieve a whitening effect on polyester fabric by utilizing a ground form of raw OB-1 (OB-1-G) in combination with dispersing agents. The whitening process parameters, such as whitening temperature, OB-1-G mass, and whitening time were optimized using the L_{16} orthogonal array-based Taguchi methodology. The signal-to-noise ratio was carried out through a larger-is-better approach to augment the parameter responses, specifically the whiteness. The results suggest that the degree of whiteness of polyester fabric is significantly affected by the whitening treatment temperature ($P < 0.05$), with a contribution percentage of 93.87%. A whiteness index of 94.12 was achieved for the polyester fabric treated at the optimized conditions. The fabric treated with OB-1-G at the optimized conditions was characterized by Fourier transform infrared spectroscopy (FT-IR), scanning electron microscopy (SEM), thermogravimetric analysis (TGA), and X-ray diffraction (XRD). The investigation also included the correlation between the length of time spent in washing and rubbing, and their efficacy in achieving whitening outcomes. The research demonstrated the effectiveness of OB-1-G nanopowder in combination with dispersing agents as a fluorescent optical brightener for the optical brightening of polyester fiber with potential use in the textile industry on a larger scale.

* Corresponding author at: Hubei Provincial Engineering Laboratory for Clean Production and High-Value Utilisation of Bio-based Textile Materials, Wuhan Textile University, Wuhan 430200, China.
** Corresponding authors.
E-mail addresses: linalin@wtu.edu.cn (L. Lin), xiongxiaorong@hgnu.edu.cn (X. Xiong), mahbubul.hassan@arts.ac.uk (M.M. Hassan).

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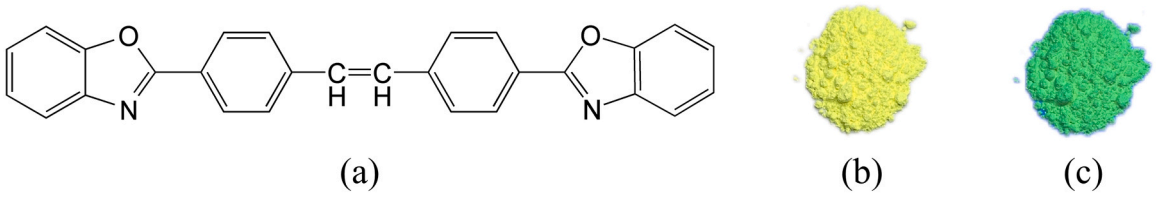

Fig. 1. Chemical structure of OB-1-G (a) and its powder irradiated under D65 light (b) and UV light (c).

1. Introduction

The fluorescent whitening agent (FWA) has the unique ability to absorb ultraviolet light ranging from 330 to 380 nm and then emit it between 400 and 450 nm, ultimately resulting in a whitening effect [1,2]. FWAs can be found in a wide range of products, such as textiles, paper, detergent, plastic, food, and cosmetics [3,4].

The yellowing of white textiles under solar irradiation is a common phenomenon. Under long-term sunlight irradiation, natural and synthetic fibers undergo photo-oxidation causing their degradation, and conjugation of degradation products forms new structures that absorb shorter wavelength light causing a yellow appearance. Chemical bleaching, whitening by using a very small dosage of blue dyes, and fluorescent whitening agents are widely used in the textile industry for the whitening of textiles. In chemical bleaching, a strong oxidant (such as hydrogen peroxide) or strong reductant (such as sodium hydrosulfite) is used, which decolorizes the natural pigments present in the fibers by oxidizing them to small chemical groups or reducing to saturated components to promote the whiteness of the fibers. However, severe oxidation in chemical bleaching can degrade the molecular chains of fibers resulting in a considerable strength loss [5]. Whitening of textiles by the addition of a very low dosage of a few blue colorants to supplement the blue tinting in the reflected light was studied, but the whitening effect was small [6,7]. Meanwhile, the brightness of the treated textile decreases due to the decrease in the total amount of reflected light. To avoid the limitations of the weakening of fabric by chemical bleaching agents and the poor brightening effect of blue tinting, whitening with fluorescent whitening agents (FWAs) is the preferable method in textile industry [8,9].

Only a small dosage of FWA (0.02–0.2% on the weight of fiber) is enough for the whitening of textiles. FWAs are considered a colorless fluorescent dye as they do not have any chromophores. Different types of textile materials require different chemical types of FWA, such as anionic FWAs for cellulose fibers, cationic FWAs for acrylic fibers, and nonionic disperse-type FWAs for polyester and cellulose acetate [10]. In the process of dyeing with disperse dyes, the fiber's color strength increases with the dye concentration until it reaches a point of saturation adsorption. However, in fluorescent whitening, the whiteness of the fabric increases with a small increase in the dosage of FWA up to a certain level, i.e., until the FWA concentration in the textile slightly exceeds the critical concentration. When the FWA in the textile exceeds the critical concentration, the whiteness tends to decline due to the quenching of fluorescence [11,12].

FWA OB-1 (OB-1, depicted in Fig. 1) is one of the most effective oxazole whitening agents. Due to its lack of toxicity, excellent chemical stability, and high heat and light resistance, OB-1 is widely utilized in plastic products [13,14]. Additionally, OB-1 is ideal for whitening polyester fibers by adding them to the spinning dope, thanks to its ability to produce a long-lasting whitening effect that withstands many cycles of washing. This molecule has high planarity, which means that Van der Waals interaction forces can easily cause OB-1 molecules to aggregate [15,16]. Thus, the process of whitening polyester fibers through an aqueous treatment is challenging due to its almost no water solubility and poor dispersion of OB-1 in water. However, for dyeing and printing of polyester fabrics, optical whitening is unnecessary, which can also cause yellowing of fabrics in the subsequent heat treatment and affect the produced shade. Therefore, the whitening of polyester is needed when a white fabric is needed for particular applications, and fabric-stage exhaustion-based whitening is preferable to serve this purpose.

The effectiveness of whitening procedures is contingent upon various factors, such as treatment time and temperature, and the whitening agent dosage used. Hence, it is crucial to establish a systematic framework for developing, implementing, and evaluating the whitening process to attain the most favorable results. The methodology known as Design of Experiments (DOE) employs a systematic approach to establish the causal connection between process inputs and outputs [17,18]. The Taguchi methodology is commonly recognized as a reliable approach because it utilizes an orthogonal array (OA) design. The Orthogonal Array (OA) is a quantitative methodology employed to identify suitable parameters and levels [19,20]. The utilization of this method yields a decrease in the number of attempts, duration of experimentation, expenses, and human physical exertion. The Taguchi methodology places considerable emphasis on the signal-to-noise (S/N) ratio and analysis of variance (ANOVA) tables to determine statistical significance [21,22]. A response table is utilized to ascertain the optimal conditions that are influenced by the most significant factors. Confirmation tests have been utilized subsequently to authenticate the feasibility of experimental designs [23–25]. Although some scholars employed Taguchi's experimental design methodology to improve the quality of textile dyeing [26–28], it was rarely used for the optimization of whitening.

This present work aims to investigate the whitening performance of polyester fabric using ground OB-1 nanopowder (OB-1-G). This work is reporting for the first time the whitening of polyester fabrics by OB-1 nanopowder via an aqueous exhaust dyeing process. The raw OB-1 powder was ground to fine nanoparticles and mixed with surfactants/dispersing agents [29], producing a nano-colloidal dispersion of OB-1-G, which was applied for the whitening of polyester fabrics by an exhaust method. The whitening process was optimized using a sixteen Taguchi orthogonal array (L_{16}) with four levels and three parameters to ensure the replicability of this work. Finally, the characterization of the treated fabrics was determined through analytical techniques, such as SEM, FTIR, TGA, and XRD.

2. Experimental

2.1. Materials and reagents

A raw fluorescent whitening agent (OB-1) and also ground nanopowder of OB-1 (OB-1-G) containing dispersing agents were supplied by Hubei Hongxin Chemical Co., Ltd. (China). A scoured polyester (PET) knitted fabric was supplied by TST Group Holding Limited (China). Nonionic detergent (Luton 500) was purchased from Dalton UK Company. Sodium perborate tetrahydrate ($NaBO_3{\cdot}4\ H_2O$, purity of $\geq$97.0% (RT)) was purchased from Shanghai Aladdin Biochemical Technology Company (China) for colorfastness to washing tests.

2.2. Whitening process of polyester fabric with OB-1-G

For the whitening of PET fabric, a nano-colloidal dispersion of OB-1-G with a solid content from 0.02% to 0.10% o.m.f (on the mass of fabric),

Table 1
Selected processing parameters and their levels.

Symbol	Parameter	Unit	Level 1	Level 2	Level 3	Level 4
A	Temperature	°C	100	110	120	130
B	OB-1-G mass	%, o.m.f.	0.06	0.07	0.08	0.09
C	Time	min	30	40	50	60

Table 2
L_{16} (4^3) orthogonal array-based experimental data with their whiteness index and S/N ratios.

Experimental number	A	B	C	Whiteness index	S/N ratio (dB)
1	100	0.06	30	78.1	37.8
2	100	0.07	40	78.5	37.9
3	100	0.08	50	78.6	37.8
4	100	0.09	60	78.8	38.0
5	110	0.06	40	79.8	38.0
6	110	0.07	30	80.3	38.1
7	110	0.08	60	80.7	38.1
8	110	0.09	50	79.4	38.1
9	120	0.06	50	87.1	38.7
10	120	0.07	60	88.7	38.8
11	120	0.08	30	82.1	38.5
12	120	0.09	40	83.9	38.5
13	130	0.06	60	92.2	39.4
14	130	0.07	50	92.2	39.4
15	130	0.08	40	91.1	39.1
16	130	0.09	30	92.1	39.1

treatment temperature from 90 to 130 °C, treatment time at target temperature from 0 to 70 min, and liquor-to-goods ratio (liquor ratio) from 10:1–90:1 was applied to investigate the whitening performance. The whitening process was carried on with an infrared dyeing machine (Ronggui Huibao Dyeing and Finishing Machinery Factory, Foshan, China). Subsequently, the whitened sample was treated in a soap solution (2 g/L of Luton 500, liquor ratio of 50:1) at 95 °C for 15 min to remove any surface-bound OB-1-G nanoparticles. Finally, the sample was dried in an oven at 90 °C.

2.3. Characterization of fabric whitened with OB-1-G

The *CIE* whiteness index (WI) of the treated polyester fabrics was measured by using a CS-650A reflectance spectrophotometer (Hangzhou Color Spectrum Technology Co., Ltd.) under D65 light and a 10° field of view. The whiteness index of PET was expressed by the average of 10 whiteness index data that was recorded at 10 random places of each fabric sample. Meanwhile, the standard deviation of these 10 whiteness index data was used to express their whitening uniformity. The FTIR spectra of the treated polyester fabrics were collected by using a Nicolet FTIR spectrometer (Nicolet iS5, Thermo Fisher Scientific, USA) using a diamond crystal. The surface of the treated polyester fabrics was examined by a field-emission scanning electron microscope (Philips SEM 515, Germany). The TGA of the sample was determined with a thermogravimetric analyzer (TGA/DSC1, Mettler-Toledo, LLC, Shanghai, China) in a temperature range of 50–800 °C under a nitrogen atmosphere at a heating rate of 10 °C min^{-1}. The XRD pattern of PET was examined by a Rigaku Ultima III X-ray diffractometer with CuKα radiation (λ = 1.54056 Å) (Tokyo, Japan) in a 2θ range of 5–80° with 0.02° step size. The particle sizes of raw OB-1 and OB-1-G in water were

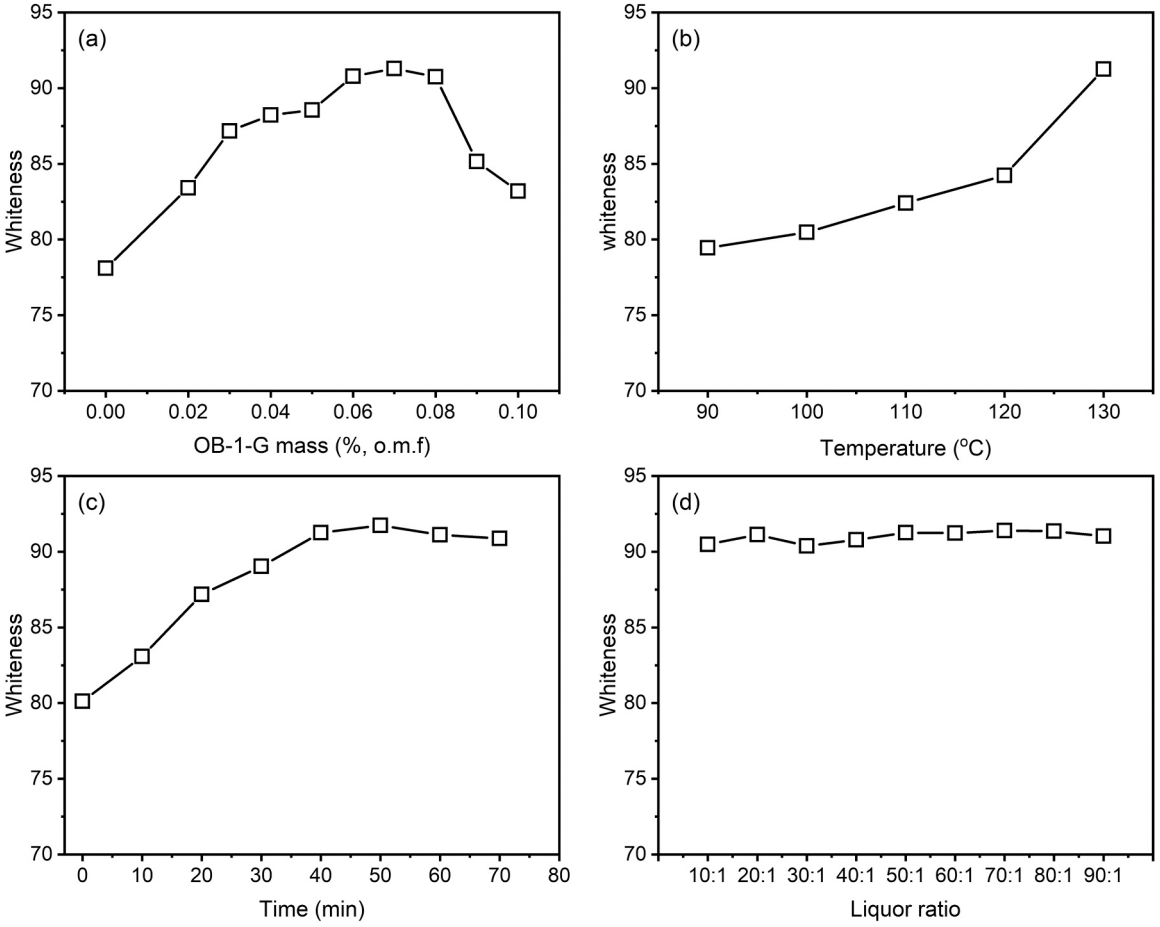

Fig. 2. Effect of OB-1-G dosage (a), whitening temperature (b), whitening time (c), and liquor ratio (d) on the whiteness index of PET fabric.

Table 3
CIE L,a*,b** values of the whitened PET fabric treated with various concentrations of OB-1-G.

OB-1-G mass (%, o.m.f)	L^*	a^*	b^*
0.07	95.13	-1.07	-0.13
0.08	94.44	-1.01	-0.73
0.09	94.67	-2.52	1.06
0.10	94.76	-3.79	1.38

detected by a Nanotrac particle analyzer (Nanotrac Wave II, Microtrac, USA). Before detection, the solution was centrifuged for 5 min at 10000 revs. min^{-1} (Cence H1650, Hunan Xiang Yi Laboratory Instrument Development Co., Ltd, China). The colorfastness to washing and rubbing was measured according to the ISO 105-C06: 2010 and ISO 105-X12:2001 standard methods, respectively.

2.4. Design of experiments

A statistical analysis utilizing Taguchi design methodology was conducted to investigate the impact of three variables on the whitening process of polyester fabric. According to the influence of OB-1-G mass, whitening temperature, whitening time, and liquor ratio of whitening solution on the whiteness index increase of PET fabric, the liquor ratio was fixed at 50:1, and the other 3 parameters were considered to design an L_{16} (4^3) array experimental scheme. The conditions of the factors in the orthogonal experimental design are listed in Table 1. The whiteness index values of the treated samples were measured, and their S/N ratio values were calculated using the "the larger-the-better" model, which is presented in Table 2. These attributes were determined by MINITAB® 20, and the details of Taguchi experimental methodology can be found freely at https://support.minitab.com/taguchi-designs.

3. Results and discussion

3.1. Effect of OB-1-G dosage (o.m.f.) on the whiteness index of fabric

The PET fabric was whitened with OB-1-G dosage ranging from 0.02% to 0.10% o.m.f at 130 °C for 40 min at a 50:1 liquor ratio, and the results are shown in Fig. 2a. The whiteness index of PET fabric gradually increased from 78.1 (original PET) to a maximum value of 91.3 for the fabric treated with 0.07% o.m.f of OB-1-G and then declined to 85.2 and 83.2 with a further increase in the dosage to 0.09% and 0.10% o.m.f, respectively. The decrease in the whiteness index was caused by the appearance of a slightly green shade at the higher dosages. The color space values of L^*, a^*, and b^* of the treated samples are listed in Table 3. The highest L^* value of the sample treated with 0.07% o.m.f is 95.13, and the others are similar. However, the a^* values decreased to − 2.52 (0.09% o.m.f) and − 3.79 (0.10% o.m.f) from − 1.07 (0.07% o.m.f), suggesting that the color shade of PET fabric changed to greenish. Also, the b^* values increased to 1.06 (0.09% o.m.f) and 1.38 (0.10% o.m.f) from − 0.13 (0.07% o.m.f), which indicates that the color shade of PET fabric changed to blueish. Therefore, the color strength on the PET fabric was greener, which caused a decrease in whitening performance with an increase in the OB-1-G dosage.

In the dyeing of polyester with disperse dyes, the dye adsorption primarily ascribes to the H-bonds and Van der Waal's force. OB-1-G exhibits the characteristics of a disperse dye because of the absence of water-solubilizing groups and due to its low molecular weight [30]. Therefore, with increasing OB-1-G dosage in the whitening treatment above 0.7% o.m.f, the excessive OB-1-G molecules were adsorbed on the PET fiber surface via Van der Waal's force and H-bond. Subsequently, the excessive OB-1-G molecules aggregated on the surface [31] and then generated a green shade because the color of OB-1-G turned green. The aggregation led to a fluorescent extinction or self-quenching, i.e.,

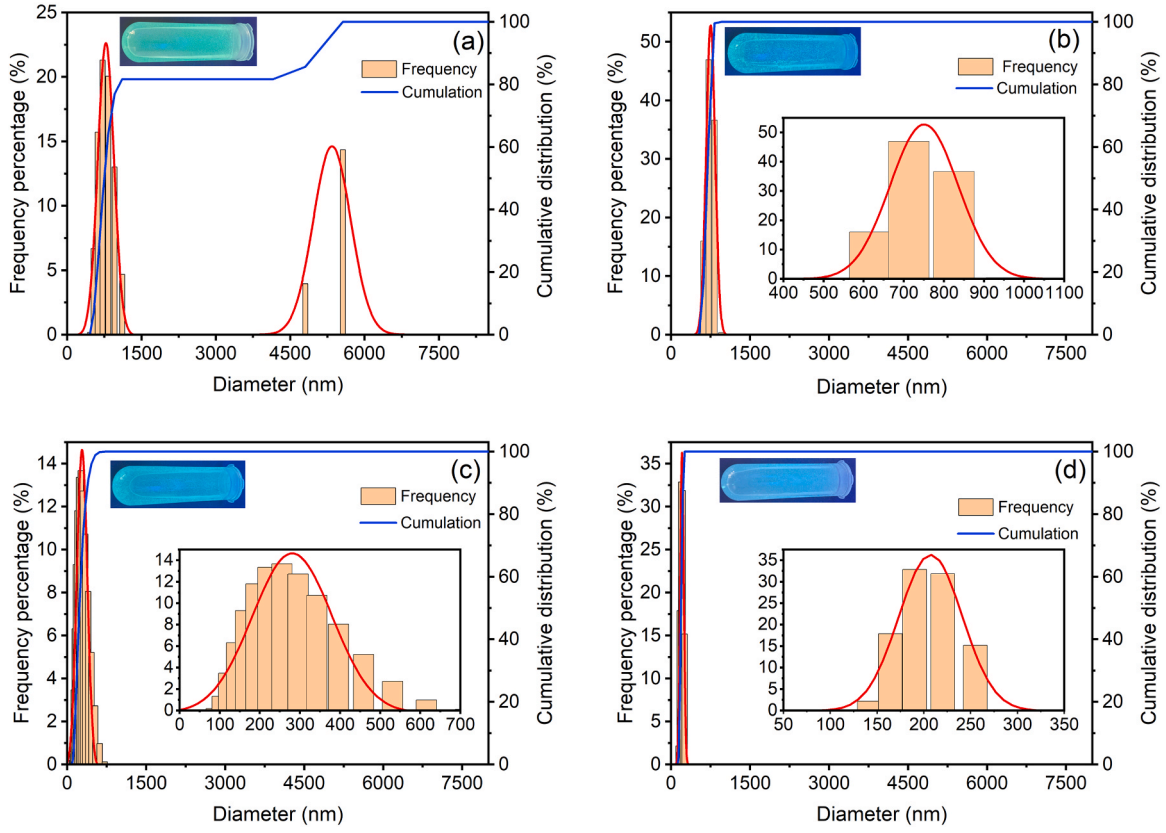

Fig. 3. The particle size of raw OB-1 in water at 130 °C (a), OB-1-G in water at 25 °C (b), OB-1-G in water at 130 °C (c), and residual whitening solution (0.06% o.m.f, 130 °C (d).

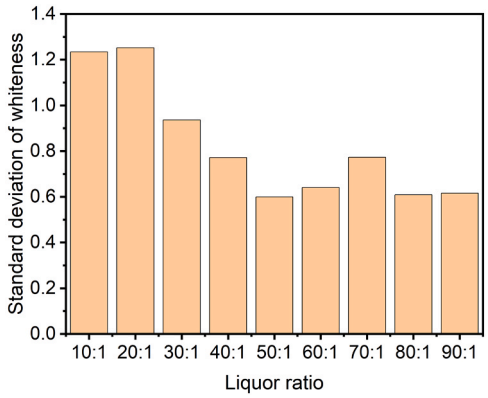

Fig. 4. Effect of liquor ratio on the whitening uniformity (standard deviation of whiteness index) of PET fabrics treated with OB-1-G in an aqueous medium.

reduction of whitening performance [32].

3.2. Effect of whitening temperature on the whiteness index of fabric

The PET fabric was whitened with 0.07% o.m.f of OB-1-G at a 50:1 liquor ratio at whitening temperatures from 90 to 130 °C for 40 min, and the results are shown in Fig. 2b. It is evident that the higher temperatures promoted the whiteness index from 79.5 at 90 °C to 91.3 at 130 °C, which is consistent with the dyeing phenomenon of polyester with disperse dyes [33] because OB-1 is similar to a disperse dye but without a chromophore. At the 130 °C of the whitening process above the glass transition temperature of the polyester fiber, the PET fiber was swollen well, and the pore sizes between PET molecular chains enlarged; simultaneously, the ground OB-1 particles well dispersed in the whitening bath solution became water soluble and transferred inside the PET fiber but again became water-insoluble and entrapped in the interior of PET fiber when the bath was cooled down.

Fig. 3 exhibits the particle size of OB-1 in various treating conditions. The particle size of raw OB-1 is distributed in two ranges (Fig. 3a), i.e., 458–1106 nm and 4800–5560 nm. Because of the flat molecular structure of OB-1, it easily aggregates and forms a bigger size particle. Thus, it hints that the difficulty of whitening PET with raw OB-1 is possibly ascribed to its big particle size. While after grinding, the particle size of OB-1-G was reduced to a range of 615–955 nm (Fig. 3b), and the increase in the treatment temperature further reduced the particle size of OB-1-G to a range of 91–712 nm (Fig. 3c). Interestingly, after the whitening treatment, the distribution of particle size of OB-1-G in the residual whitening solution was narrowed in a range of 142–255 nm (Fig. 3d). In addition, the color of the residual whitening solution in UV light is blue (fluorescent role), which distinguishes it from the green color of other samples. Thus, the result of particle size analyses is beneficial for the explanation of the high whiteness index obtained at a high treatment temperature (at 130 °C).

Based on the increased trend of whiteness, it can be assumed that whitening at 140 °C promotes the whiteness of PET further. However, PET dyeing equipment is usually designed for a maximum temperature of 130 °C, and the whitening performance of PET at 140 °C was not considered in this research.

3.3. Effect of whitening treatment time on the whiteness index of fabric

The PET fabric was whitened with 0.07% o.m.f of OB-1-G at a liquor ratio of 50:1 and 130 °C for various whitening times from 0 to 70 min, and the results are shown in Fig. 2c. By extending the whitening treatment time at 130 °C, the whiteness of PET fabric gradually increased. The whiteness index increased to a maximum value of 91.7 for 50 min from 80.1 for 0 min. During the whitening process, the adsorption of OB-1-G into PET fiber and desorption occurred simultaneously. In the initial whitening stage, the adsorption was primarily due to many small OB-1-G particles dispersed in the solution. Subsequently, with increasing the treatment time, the adsorption and desorption rates were supposed to be close, reaching equilibrium at 50 min

Table 4
Response table for S/N ratios for whitening of PET fabric with OB-1-G.

Level	A	B	C
1	37.90	38.50	38.38
2	38.07	38.56	38.40
3	38.63	38.38	38.50
4	39.27	38.42	38.58
Delta	1.37	0.18	0.20
Rank	1	3	2

3.4. Effect of liquor ratio on the whiteness index of fabric

The PET fabric was whitened with 0.07% o.m.f of OB-1-G at 130 °C for 50 min at various liquor ratios from 10:1–90:1, and the whitening results are shown in Fig. 2d. Generally, the liquor ratio of the treating process mainly contributes to the uniformity of treatment. The whiteness index values of the whitened PET fabrics treated at different liquor ratios were similar, which fluctuated in a range of 90.4–91.4. Thus, the distinct whiteness was ignorable. The whitening uniformity of the treated sample, expressed as the standard deviation of the whiteness index (STD-W), is shown in Fig. 4. Generally, the value of STD-W decreased with an increase in liquor ratio and reached a minimum (0.60) at a 50:1 liquor ratio, indicating the best uniform whitening performance was achieved at that liquor ratio [34].

3.5. Taguchi model analysis

3.5.1. S/N ratio assessment

The delta statistics, S/N ratios, were used in designing these response values, which were calculated by subtracting the maximum and minimum S/N ratios from the average values for each component [35,36], as shown in Table 4. The largest delta (1.37) was seen for the whitening temperature (A), followed by the whitening time (C) (0.20) and the OB-1-G mass (B) (0.18), which indicates that the whitening temperature primarily influenced whitening performance followed by the whitening time and the OB-1-G mass.

Fig. 5 also shows the major impacts plot of the process parameters for S/N ratios for the whitening of polyester fabric. The productivity of different process parameters is indicated by comparing their values to a straight line. An insignificant effect on the whitening procedure is indicated if a process parameter is close to the solid line. Contrarily, a parameter with a steeper slope has a more significant impact on the treatment procedure. Therefore, among the assessed factors, whitening temperature (A) was demonstrated to have a statistically significant effect on whiteness, while OB-1-G mass (B) and whitening time (C) had a very small impact on whiteness.

3.5.2. Assessment of interaction plots

Fig. 6 illustrates a marked interaction, with four lines intersecting at varying degrees between all process variables and the whiteness of the PET fabric. Since the whitening temperature variable (A) majorly influenced the whiteness, i.e., the distinction between temperatures is far more than that between OB-1-G masses (B) or whitening time (C). Thus, the relationship between whitening temperature (A) and OB-1-G mass (B) or between whitening temperature (A) and whitening time (C) is not correlated. Inversely, the variables of OB-1-G (B) mass and whitening time (C) are correlated, although both negligibly influence the whitening performance, compared to the whitening temperature (A).

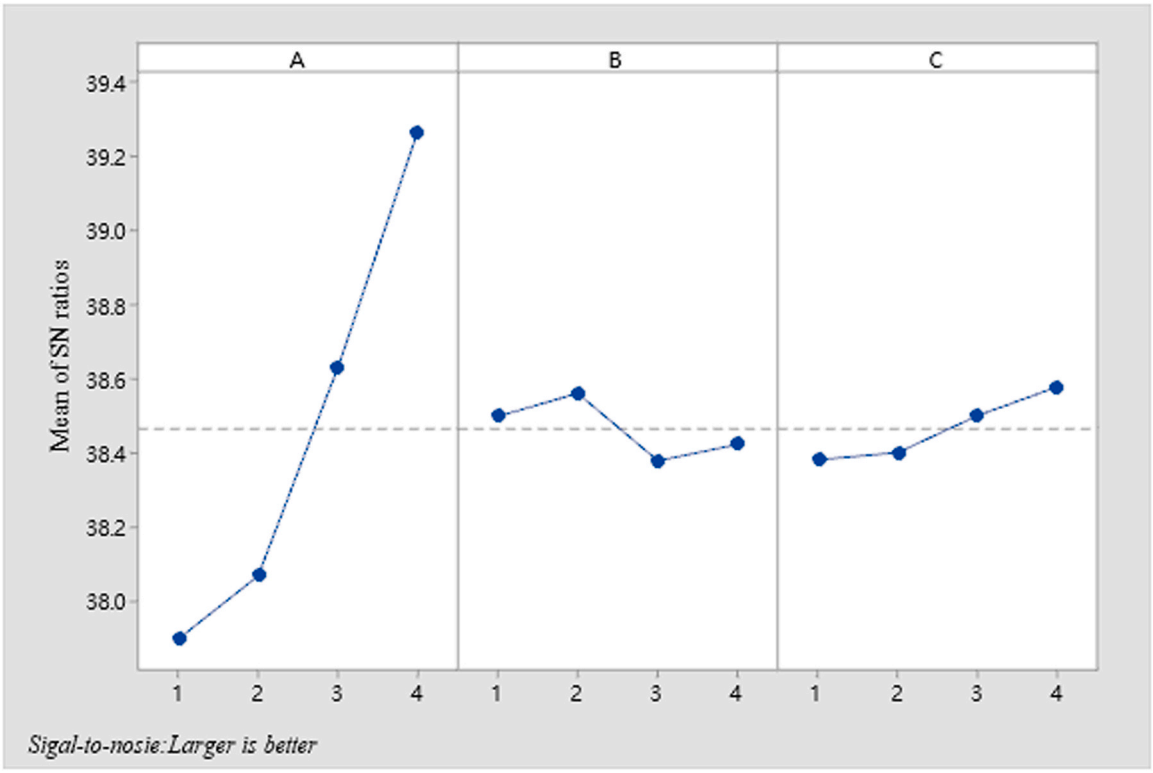

Fig. 5. Main effects plot for S/N ratios for whitening of PET fabric with OB-1-G.

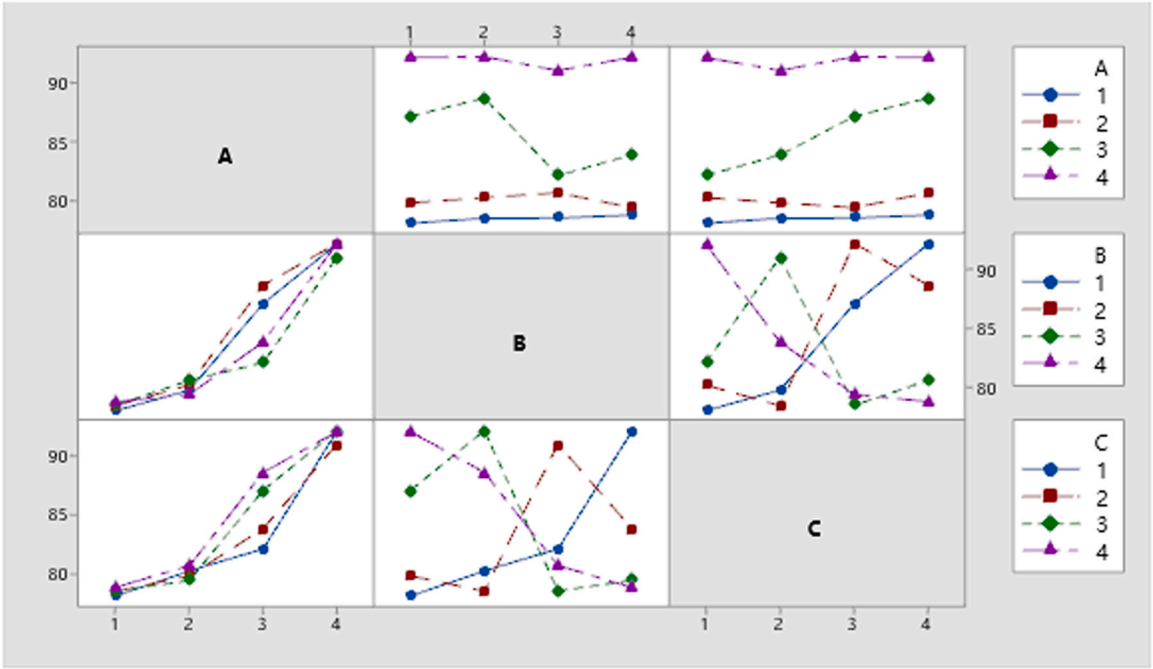

Fig. 6. Full interaction plot for S/N ratios for whitening of PET fabric with OB-1-G.

3.5.3. ANOVA

Table 5 displays the use of ANOVA to identify the process characteristics that had a statistically significant effect on whiteness efficiency, along with their confidence levels and interactions. It was concluded that an elevated whitening temperature considerably affected whiteness performance, as evident by a high F-value of 78.04 and a p-value of 0.000 (statistically significant). However, other factors, such as the mass of OB-1-G and the whitening time, have F-values of 1.37 and 1.72, respectively, and are considered statistically insignificant with p-values above 0.05 (around 0.338 and 0.262, respectively).

Moreover, the percentage contribution (P%) of each factor or interaction between variables represents the proportion of the total variation of experimental results attributable to that component. Table 5 depicts the P% data for each factor, indicating that the whitening temperature

Table 5
ANOVA of S/N ratios for whitening of PET fabric with OB-1-G.

Source	DF	SS	MS	F	p-value	Remarks	P (%)
A	3	440.176	146.725	78.04	0.000	Significant	93.87
B	3	7.739	2.580	1.37	0.338	Insignificant	1.65
C	3	9.705	3.235	1.72	0.262	Insignificant	2.07
Residual Error	6	11.281	1.880				2.41
Total	15	468.901					

Table 6
Validation tests.

Conditions	Initial parameters	Prediction	Confirmation experiment
Level	A4B2C3	A4B2C4	A4B2C4
Whiteness index	92.20	93.94	94.12
S/N	39.40	39.47	39.47
Improvement in the S/N ratio		0.07	

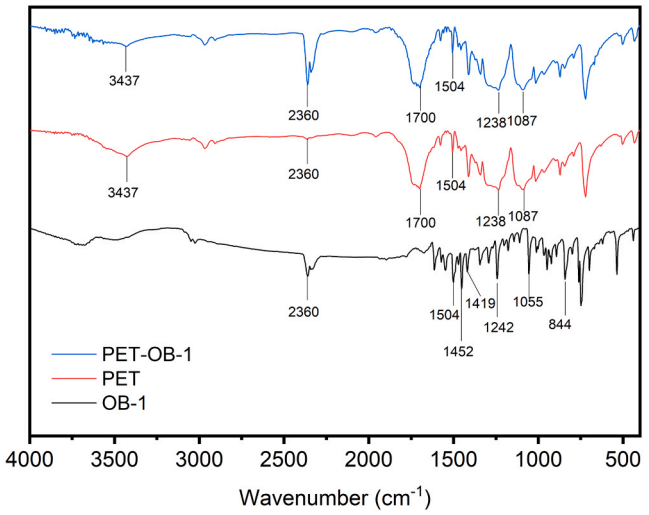

Fig. 7. FT-IR spectra of OB-1-G, PET, and PET-OB-1-G.

was the most significant contributor, accounting for approximately 93.87% of the overall variation. The contribution of the whitening time and OB-1-G mass was 2.07% and 1.65%, respectively, demonstrating that the whitening temperature had the most substantial impact on whiteness, followed by OB-1-G mass and whitening time.

3.5.4. Validation

The Taguchi methodology necessitates the execution of a validation examination to provide further insight into the obtained results. For statistical methodologies, it is highly advised to conduct such a test. The principal objective of this inquiry is to ascertain the reliability of the questionnaires and responses [37]. Table 6 provides a comprehensive account of the outcomes obtained from the validation experiments. Once the parameters for achieving optimal performance have been identified, the subsequent step involves verifying the effectiveness of the enhanced process. The predicted values were calculated and determined using the MINITAB® 20 software. Consequently, the experiment was conducted utilizing optimal parameters that significantly enhance the signal-to-noise ratio. The primary aim of the present investigation was successfully achieved, as evidenced by the observed augmentation in whiteness (resulting in a corresponding rise in the signal-to-noise ratio of 0.07). Based on the findings, it is suggested that optimal outcomes could be achieved through the implementation of an experimental design that consistently adheres to statistical standards.

3.6. FT-IR analysis

Fig. 7 displays the FT-IR spectra of raw OB-1, PET, and whitened PET fabric (0.07% o.m.f of OB-1-G at 130 °C for 50 min, PET-OB-1). The characteristic peaks of the FT-IR spectrum of OB-1 at 1504 cm^{-1} and 1452 cm^{-1} correspond to the bending vibration bonds of C=C in the phenyl ring, while the peak at 844 cm^{-1} corresponds to the vibration C-

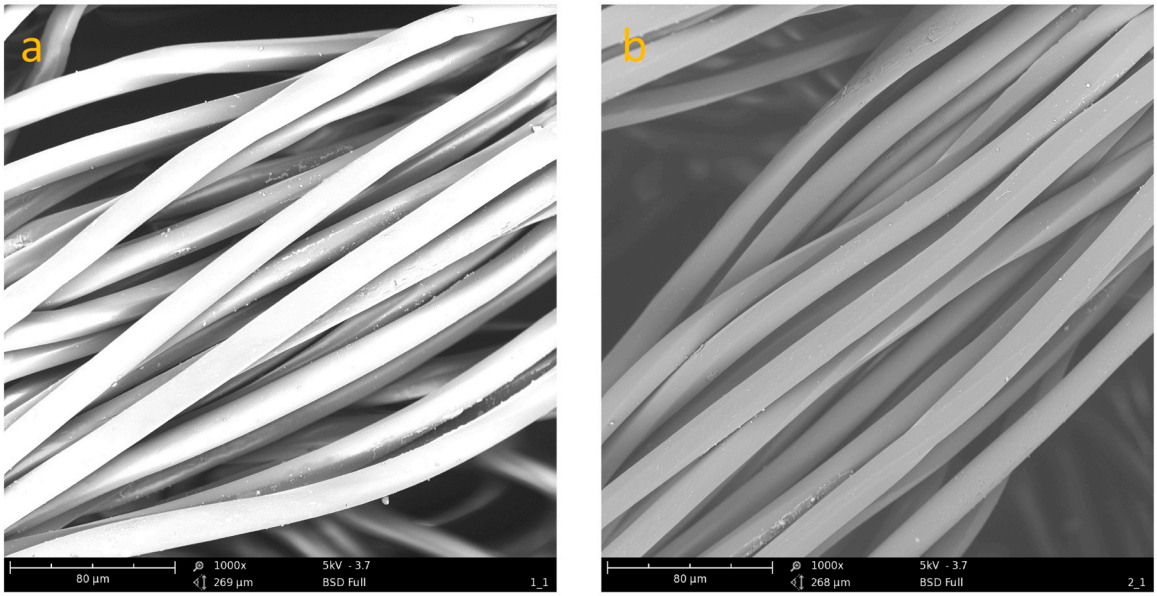

Fig. 8. SEM images of PET fabric with 2000 magnification (a) and PET-OB-1-G fabric with 2000 magnification (b).

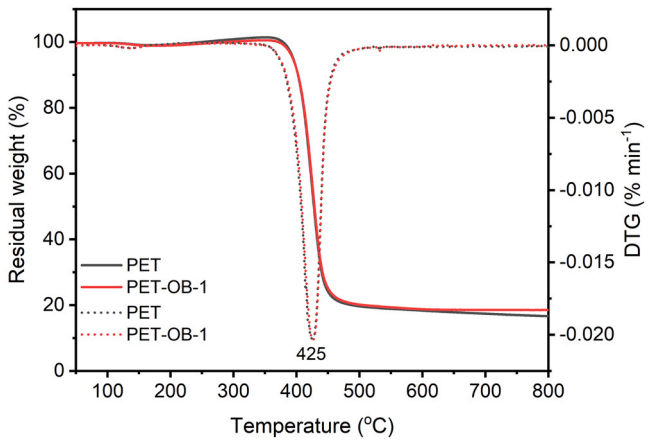

Fig. 9. TG and DTG curves of the PET and PET-OB-1-G fibers.

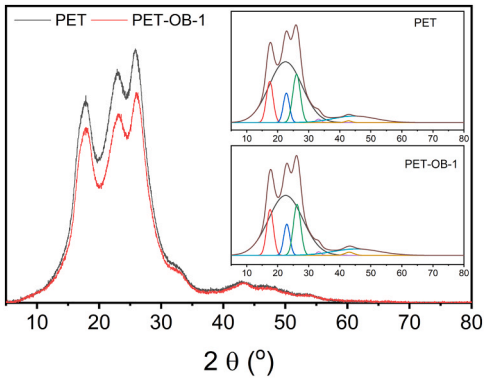

Fig. 10. XRD patterns of the PET and PET-OB-1-G fabrics.

H bonds of the phenyl ring. The bending vibration bond of -C═N (1420 cm^{-1}) and the stretching vibration bond of -C-O (1242 cm^{-1} and 1055 cm^{-1}) have been previously identified [38]. The characteristic peaks of the ester linkage in PET appear at 1700 cm^{-1} (stretching vibration band of C═O) and at 1087 cm^{-1} and 1238 cm^{-1} (C-O-C stretching vibration band). The stretching vibration of unreacted hydroxyl groups in PET exhibits weak broadband in the region 3437 cm^{-1} [39]. The peak at 1504 cm^{-1} indicates the symmetric structure of the benzene ring [40]. PET-OB-1′s FT-IR spectrum closely resembles PET since the low concentration of OB-1-G in PET was undetectable.

3.7. Surface topography analysis

Fig. 8 displays the surface topographies of PET and PET-OB-1-G fibers, as investigated by SEM. The SEM images of both fibers demonstrate a uniform and seamless surface without any erosion, suggesting that the whitening treatment did not cause surface damage. Additionally, the unblemished surface of PET-OB-1-G suggests that the planar molecular structure of OB-1-G did not amalgamate or coalesce into large particles on the fiber surface but was absorbed into the fiber.

3.8. Thermogravimetric analysis

Thermogravimetric analysis was carried out to assess the thermal stability of OB-1-G inside polyester fiber (Fig. 9). The thermal decomposition patterns of the PET remained consistent before and after whitening, with thermal decomposition commencing at 340 °C, and the maximum decomposition rate occurring at 425 °C, before reaching stable decomposition at 490 °C. Nonetheless, the residual weight percentage of PET increased slightly after whitening, possibly due to the presence of OB-1-G in the PET.

Table 7
Crystallite parameters of PET fabric treated with OB-1-G.

Sample	2θ of peak (°)	d (Å)	FWHM (°)	S (Å)	CI (%)
PET	17.4	5.09	2.61	30.42	26.3
	22.8	3.90	2.32	34.58	
	26.1	3.41	2.87	28.14	
PET-OB-1-G	17.5	5.05	2.62	30.31	26.9
	22.9	3.87	2.33	34.47	
	26.2	3.39	2.79	28.97	

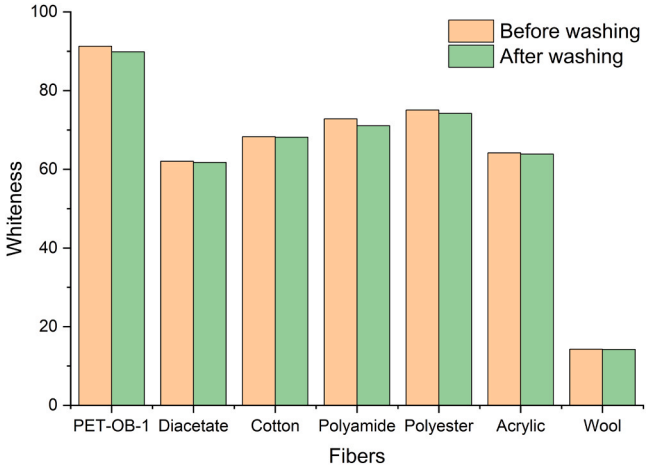

Fig. 11. The whiteness index of the whitened PET fabric and the multifiber fabric before and after the washing test.

3.9. XRD analysis

Fig. 10 depicts both samples' XRD patterns and the corresponding deconvolution of PET and PET-OB-1-G, demonstrating similar diffraction peaks and shapes. The parameters of crystallinity, including interplanar spacing (d), crystallite size (S), and crystallinity index (CI), were calculated using Eq. 1 [41], Eq. 2 [42], and Eq. 3 [43], respectively, and listed in Table 7.

$$d = \frac{\lambda}{2\sin\theta} \quad (1)$$

$$S = \frac{0.89\lambda}{\beta\cos\theta} \quad (2)$$

$$CI = \frac{A_C}{A_C + A_A} \times 100\% \quad (3)$$

Where λ is CuKα radiation (λ = 1.54056 Å), θ is Bragg angle, and the radian of full width at half maximum (FWHM) is denoted as β. Additionally, A_C and A_A represent the crystallinity and amorphous areas of the sample, respectively.

Both samples display main diffraction crystallinity peaks at around 17.4 °, 22.8 °, and 26.1 °, corresponding to 3 crystal planes (010), ($\bar{1}$01), and (100), respectively [44]. The interplanar spacing and crystallite size are consistent with published results [45] and the detailed results are provided in Table 7. The CI of PET and PET-OB-1-G were 26.3% and 26.9%, respectively, which aligned with their XRD diffraction profile [46]. The slight differences in CI values were negligible, thus demonstrating that OB-1 whitening in a water medium did not alter the morphological structure of PET [47].

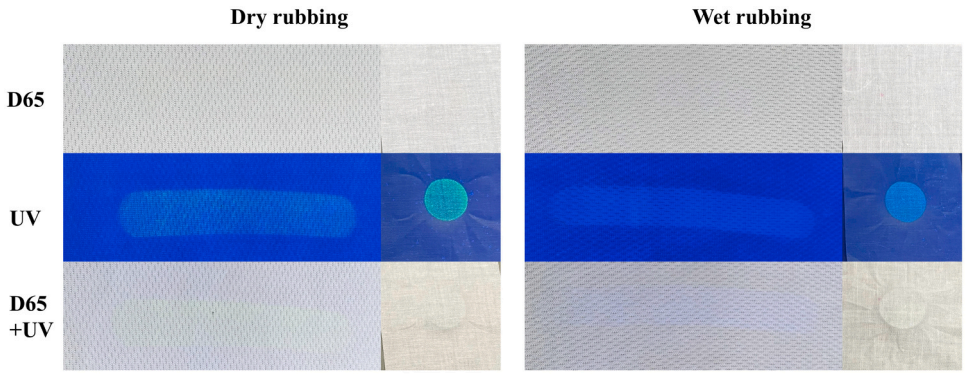

Fig. 12. Optical images of whitened fabrics after dry and wet rubbing tests under D65, UV, and D65 +UV lights.

Table 8
Colorfastness to washing and rubbing of fabric whitened with OB-1-G.

Condition	Fabric	Whiteness	Colorimetric values of the test fabric		
			L*	a*	b*
Before rubbing	PET	91.3	91.95	-0.63	-0.31
	Cotton	70.5	94.03	-0.35	3.48
Dry rubbing	PET	88.6	91.56	-0.72	-0.91
	Cotton	64.4	91.22	0.31	2.87
Wet rubbing	PET	87.1	90.51	0.25	-2.66
	Cotton	62.3	90.95	-0.30	3.20

3.10. Colorfastness to washing and rubbing

After the washing test, the whiteness of the sample and the multifiber fabric were measured and shown in Fig. 11. First, the whiteness of the sample after the washing testing is close to the whiteness of the fabric before washing, and it is the same as the multifiber fabric (Fig. 12). Thus, it indicates that the treated fabric has a high colorfastness to washing and will not cause any staining to other fibers when will be washed with them [48].

The whiteness index of PET fabric slightly decreased to 88.6 and 87.1 for dry rubbing and wet rubbing from 91.3, respectively, after the colorfastness to rubbing test as shown in Table 8. After dry and wet rubbings, the rubbing tracks on the PET surface were clear under UV light but normal under D65 light. The colors of the rubbing track after dry rubbing and wet rubbing were green and light blue shades, which were easily distinguished under the lights of D65 and UV. The corresponding color space L* , a* , and b* values of the rubbing track and the test cotton fabric are listed in Table 8, and the samples are shown in Fig. 12.

The cotton test fabric was stained by OB-1-G, and its whiteness declined from 70.5 to 64.4 and 62.3 after dry rubbing and wet rubbing tests, respectively. The original color of the raw OB-1 particle was green, so it can be speculated that after dry rubbing, the OB-1-G transferred from the PET sample to test cotton fabric, and aggregated on its surface, resulting in a self-quenching of fluorescence. Thus, the color of the rubbing track on PET and the test cotton fabric appeared green shade. By contrast, the OB-1-G molecules obstruct aggregation on wet fabric surfaces during wet rubbing. Thus, the color of the rubbing track on PET and the test cotton fabric was light blue, i.e., light fluorescence. These factors changed the colorimetric values of the cotton test fabric, slightly decreasing whiteness [49,50].

4. Conclusions

The current investigation has introduced a novel approach to improve the whitening efficacy of polyester fabric by utilizing nano to microparticles of OB-1-G by an aqueous exhaust treatment. The utilization of the Taguchi methodology enabled the identification of optimal conditions for the whitening of polyester fabric with OB-1-G. The conditions identified as the most favorable are denoted as A4B2C4, i.e., a whitening temperature of 130 °C, an OB-1-G mass of 0.07% o.m.f, and a whitening duration of 60 min. Following this, ANOVA was performed, which revealed that the predominant factor contributing to the observed result was the temperature and at 130 at °C the optimum whitening was achieved. We investigated the phenomenon of whiteness under ideal circumstances, uncovering a higher proportion (94.12) relative to the baseline conditions (92.20). The aforementioned result can be attributed to the photographic depiction of the specimens that underwent treatment with OB-1-G. The findings from the analytical characterization suggest that PET fiber's morphological structure remained unchanged after the whitening treatment with OB-1-G whitening in an aqueous medium. In addition, the achieved colorfastness to washing and rubbing exhibited by the fabric whitened with OB-1-G was satisfactory. The achieved results had a significant degree of coherence and replicability; thereby presenting a promising, robust, and sustainable optical brightening method for polyester fabric using ground OB-1-G powder. The developed method could be a sustainable alternative to the currently used toxic optical brightening agents used in the textile industry for the optical brightening of polyester fabrics.

CRediT authorship contribution statement

Conceptualization, Yingjie Cai, Lina Lin, Xiaorong Xiong.; **Formal analysis, Writing – original draft, Final paper preparation,** Yingjie Cai, Le Li, Tianjie Wang, Ying Ren, Md. Nahid Pervez, Ai Chen, Xiaohua Zhao.; **Writing – review & editing,** Yingjie Cai, Md. Nahid Pervez, Mohammad Mahbubul Hassan.; **Project administration, Funding acquisition, Supervision,** Lina Lin, Xiaorong Xiong, Mohammad Mahbubul Hassan. All authors have read and agreed to the published version of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Acknowledgments

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