



## OPEN Contamination of fabric surface by the particles woven from the cotton waste open end rotor yarn

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The study investigated and analyzed the contamination of the fabric surface due to cotton waste yarn woven into the weft. The impact of cotton waste proportion and cleaning methods on open-end rotor yarn quality, using blends from 100 to 0% cotton waste mixed with virgin cotton fibers were investigated. The study proves that cotton waste can be effectively incorporated into yarn production without significantly compromising fabric properties, supporting the sustainable use of recycled fibers. The innovative cleaning channel W increases fiber yield but also raises contamination levels, leading to a higher number of detected impurities on the fabric surface. The classification method for dust and trash particles significantly affects the contamination evaluation, though contamination trends remain consistent. The classification of dust and trash particles by the maximal Ferret's diameter is preferred based on the obtained outputs from the realized experiment. Additionally, while the size of dust particles decreases as the cotton waste proportion decreases, trash particle size is unaffected by the cleaning channel or waste ratio in the weft yarn. In the case of the binary portion, contaminant levels decrease as cotton waste content in weft yarns is reduced, with the lowest found in cleaning channel A, followed by C and W. Surprisingly, dust and trash particles contribute to the binary portion equally. It leads to the recommendation connected with optimizing fabric quality, the final treatment should focus mainly on eliminating the visual impact of larger contaminants. The reason is that smaller particles can be mostly removed during pretreatment because they are not firmly fixed in a woven structure. The results also highlight the link between fabric contamination and potential health risks from respirable dust particles in the workplace, underscoring the need for effective control during processing to protect workers and ensure stable production not only in weaving but also in the following processes.

**Keywords** Open-end rotor cotton spun yarn, Cotton waste, Trash and dust, Trash count and dust count, Image analysis, Contamination of fabrics by seed coat fragments

Cotton fiber is still the main natural fiber used in textile production. The lack of sources and the environmental impact of cotton production are leading to a greater awareness of sustainability in this industry sector and an emphasis on waste reduction and its potential reuse. The importance and the way and impact of textile waste recycling is declared e.g. in articles<sup>1-4</sup>. The scientific teams of Damayanti, Duhoux, Esteve-Turrillas and Sandin explores textile recycling routes, potential and relevant recycling technologies, key challenges, and innovations advancing a circular economy as well as describe the life cycle assessment approach. Moreover, Duhoux and all give the context to the Green Deal policy, relevant technologies and their capacity in Europe and publish it in<sup>2</sup>.

The quality of cotton fibers is significantly influenced by the way they are processed, and it is important to optimize all processes in the transformation chain from fiber material through yarn to the final products, in order to close the loop of upcycling cotton waste. The results for woven and knitted fabrics produced from recycled cotton waste is presented for woven or knitted fabrics by Telli, Yüksekakaya and Gun et al in<sup>5-7</sup>. The importance of preselecting the setting of the whole production line from fibers through yarn to the final product mainly for open end rotor spinning is realized in many studies. For example, Ute et al explored how waste type and blend ratio affect yarn and fabric properties, promoting resource efficiency and cost reduction in textile manufacturing in<sup>8</sup>. Hallimi et al in<sup>9</sup> studied the impact of cotton waste and spinning parameters on rotor yarn quality. Hassani et al in<sup>10</sup> optimized rotor spinning parameters to minimize yarn hairiness when producing cotton yarn from ginning waste, identifying rotor diameter and navel type as the most influential factors, while the opening roller speed had minimal impact. Similarly, Kaplan et al analysed the impact of various navel

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properties on the quality of rotor yarns spun from 100% cotton waste, pointing out that steel navel achieved the best evenness and imperfection values, while spiral ceramic navel improved hairiness, tenacity, and elongation due to reduced yarn deformation<sup>11</sup>.

Processing cotton waste, whether pre-consumer or post-consumer, presents two challenges. One is the optimization of the various stages of production, from the fiber to the yarn and the final product. The other is to monitor and limit any deterioration in the safety of the working environment during production due to the release of increased amounts of dust or trash particles included in cotton waste and fiber fragments, which increase the need for maintenance in terms of cleaning and services of parts. Occupational exposure to textile dust has been linked to various respiratory conditions, including byssinosis, which is characterized by chest tightness and other pulmonary<sup>12–14</sup>. Long-term exposure to cotton dust has been shown to result in chronic respiratory impairments, highlighting the importance of managing dust levels in textile manufacturing<sup>12</sup>. Additionally, studies have indicated that textile dust can exacerbate allergic reactions, further complicating the health implications for workers in this industry<sup>15,16</sup>.

The processing of cotton waste can bring savings, but the potential impact on the working environment has to be minimized too. The first spinning strategy adopted by companies focuses on processing pre-consumer industrial cotton waste, where the raw material primarily consists of virgin cotton fibers and noils or fibers recovered from the spinning process, typically in amounts ranging from 0 to 15% waste content. It is primarily oriented to maximize the quality of semi-products and final yarns, ensuring that the fibers retain their optimal length and minimal contamination. This is achieved by prioritizing the removal of dust and impurities over fiber retention, making this strategy ideal for producing high-quality yarns. In contrast, the second strategy is designed for processing industrial post-consumer waste, textile scraps, and hard-to-recover spinning waste, which tend to have shorter fibers and higher contamination levels. Here, the focus is on minimizing fiber loss, meaning that fiber holding is prioritized over impurity removal. As a result, this approach allows for higher waste utilization, but it may also lead to lower yarn quality, characterized by unevenness, hairiness, faults, and a rustic appearance due to the incorporation of plant particles into the yarn structure.

The innovative cleaning method, which allows the selection of the spinning strategy for the production of open-end rotor yarn on Rieter R 37 Rotor spinning machine, is part of a wider research work. The initial outcomes from the early stages focused on processing cotton waste with high amounts of impurities are described in<sup>17</sup>. The comparative study for yarn produced from virgin cotton and extremely contaminated cotton waste with relatively short fiber length was realized to find the limits for setting the whole spinning line and analyze the impact on the quality of open-end rotor yarns. The follow-up study oriented to the evaluation of the potential influence of blending portion of cotton waste and a cleaning channel used on the quality of rotor open-end yarns for a set of 29.5-tex yarns in gray and dyed form is published in<sup>18</sup> and for a set of 98-tex is presented in<sup>19</sup>. The results confirmed that fiber quality, sliver preparation, and used cleaning channels during spinning significantly impact yarn quality, mainly those spun from 100% cotton waste. On the other hand, also the yarns spun under similar conditions from cotton waste only have to still be sufficient for preselected final application with respect to USTER STATISTICS quality standards for specific final use in fabric structure. It allows manufacturers to optimize waste removal, maintain fiber yield, and optimize costs.

The next step to move the topic further was to ensure how the quality of yarn impacts the quality of fabric in a gray state and after final treatment. The earlier research demonstrated that highly contaminated cotton waste could be effectively processed into open-end rotor yarns using specific cleaning channels, with comparable yarn quality achieved for the most yarn count used in the market (29.5-tex and 98-tex yarns) despite variations in fibre length, short fibre content, and impurity amount. While cleaning channel W improved fibre utilization, it resulted in higher yarn contamination, particularly in terms of trash and dust particles. When woven into fabrics and subjected to pre-treatment, bleaching, and home washing, contamination decreased, and fabric quality remained stable, with no significant surface changes after abrasion. These findings confirmed that by selecting an appropriate spinning and cleaning strategy, cotton waste can be efficiently utilized to produce yarns and fabrics for specific final use with the optimal level of their quality.

To further investigate the effect of cotton waste blending proportions and used cleaning channels during spinning, the follow-up planned experiment was conducted to assess not only their effect on yarn quality but also their influence on fabric, mainly in terms of its surface contamination by seed coat fragments. The contamination of the cotton raw fiber material is usually determined by the optical principle, which is realized by using the Trash tester or USTER AFIS PRO<sup>20</sup>. The USTER TESTER 5<sup>21</sup> or higher is a complex system for the determination of yarn quality, including the evaluation of impurities. Based on the optical principle, it is possible to monitor the number of impurities in 1 km of yarn for dust impurities and foreign particles, mainly plant residues or seed coat fragments. Methodologies applied for fabric contamination are not widely spread in the industry, and most of the existing techniques exist only in lab-scale format. The technique based on image analysis is introduced by e.g. by Li, Bel et al. in<sup>22–24</sup>. These procedures are based on the scanning of fabric images and their processing; the thresholding is realized by the adoption of the color difference of seed coat fragments.

### Manuscript aim

The objective of this study is to assess the impact of cotton fibre quality on the quality of yarns and fabrics, surface quality produced from them, with a particular focus on the degree of contamination. The research examines existing methods for evaluating contamination levels in raw cotton, yarns, and fabrics, aiming to identify and propose suitable qualitative and quantitative parameters for assessing impurities, particularly seed coat fragments and other plant residues. Furthermore, the study evaluates the significance of the blend ratio of reused cotton fibers and the cleaning processes applied during spinning, analysing their effects on yarn quality and the resulting contamination of fabrics in a gray state. The findings aim to contribute to the optimization of contamination assessment methods and quality control strategies in textile production and indirectly contribute

Material type	CO waste 100%	CO waste/CO 75%/25%	CO waste/CO 50%/50%	CO waste/CO 25%/75%	CO 100%
$L_{(w)}$ [mm]	21	21.7	22.7	23.1	23.6
CV $L_{(w)}$ [%]	40	38.4	36.5	35.5	34
$UQL_{(w)}$ [mm]	26.9	27.6	28.5	29.0	29.3
$SFC_{(w)}$ % < 12,7	17.2	15.0	12.2	11.3	9.8
$Neps$ [Cnt g <sup>-1</sup> ]	412	289	196	138	74
$Dust$ [Cnt g <sup>-1</sup> ]	1004	711	486	350	146
$Trash$ [Cnt g <sup>-1</sup> ]	122	92	50	32	9

**Table 1.** Selected qualitative parameters of fiber blends.

Fiber blend	CO waste 100%	CO waste/CO 75%/25%	CO waste/CO 50%/50%	CO waste/CO 25%/75%	CO 100%
$T_{sliver}$ [tex]	6000	6000	6000	6000	6000
$T_{yarn}$ [tex]	29.5	29.5	29.5	29.5	29.5
Draft	203	203	203	203	203
Twist [m <sup>-1</sup> ]	985	932	901	827	796
Phrix twist coeff. [ktex <sup>2/3</sup> m <sup>-1</sup> ]	94	89	86	79	76
Rotor RPM [min <sup>-1</sup> ]	100,000	100,000	100,000	105,000	110,000
Opening roller RPM [min <sup>-1</sup> ]	10,000	10,000	10,000	9500	9000
Delivery speed [m min <sup>-1</sup> ]	102	107	111	127	138
Cleaning channel	A, C, W	A, C, W	A, C, W	A, C, W	A, C, W

**Table 2.** Rieter R37 machine settings.

to the knowledge of the amount of impurities that may have been released into the environment during the processing of cotton waste yarns into fabrics.

Seed coat fragments are typically present in low amounts in virgin cotton or are removed during fiber pre-processing as part of the overall spinning setup, as exemplified by Strategy 1. However, when highly contaminated cotton waste is utilized, particularly in the case of Strategy 2, it becomes essential to assess the extent to which impurities, especially seed coat fragments, remain fixed in the yarn and potentially affect fabric quality during the following processes. Cotton waste recovered from blow-room operations can contain significant levels of dust and trash particles. Furthermore, a gap in the current literature has been identified: no comprehensive study has yet compared fabric contamination resulting from cotton waste yarns with varying impurity levels. Prior studies and practical experience have shown that seed coat fragments may remain incorporated in the yarn structure. To prevent deterioration in fabric quality, these residual fragments must undergo chemical decolorization, making appropriate pre-treatment and bleaching necessary to achieve the desired color quality in the final fabric<sup>22,23</sup>.

## Materials and methods

### Selection and production of open-end rotor yarn from cotton waste

The impact of cotton waste proportion and cleaning methods on open-end rotor yarn quality, using blends of 100–0% cotton waste mixed with virgin cotton fibers, was investigated. The blowroom waste (mixture of waste from fibre pre-treatment, cleaning and mixing, flat stripes, hard card waste, remains of sliver from doubling and drawing, and noils) was blended with virgin cotton fibers. The fiber blends underwent standard pre-treatment, mixing, and carding before being spun on a Rieter R37 spinning machine. The selection of the cleaning channel allows the producers to select the optimal spinning strategy. Channel A prioritizes high yarn quality, removing both impurities and some good fibers, resulting in higher waste generation (spinning strategy 1). Channel C optimally removes impurities and fiber neps, suitable for low-contamination raw materials (spinning strategy 1). Channel W minimizes waste and maximizes fiber yield but increases contamination risks, leading to a more rustic yarn appearance (spinning strategy 2).

To determine the optimal yarn construction parameters and spinning settings, fiber quality was assessed based on standard length parameters (fiber upper quantile  $UQL_w$  length, mean length  $L_w$ , and short fiber content  $SFC_w$  measured by weighting method) and fiber contamination ( $Neps$ ,  $Dust$ ,  $Trash$ ) was conducted on samples taken from slivers using the USTER AFIS PRO<sup>20</sup>. The details about the fiber quality are shown in Table 1.

The optimum spinning settings of Rieter R 37 open-end rotor spinning machine were selected (rotor type S533, draw-off nozzle SR7 KS, spinning pressure 6 kPa) to produce 25 yarn samples with a count of  $T_{yarn} = 29.5$  tex and a suitable twist  $Z$ , which increased as the percentage of cotton waste increased. The details about the spinning machine setting are summarized in Table 2.

The qualitative structure, mechanical properties, abrasion resistance, and lint generation during yarn-on-yarn abrasion were assessed to determine how factors such as waste portion, fiber quality, cleaning method, and twist level influence overall yarn quality. The typical yarn structural and mechanical characteristics were

evaluated together with the yarn abrasion resistance and lint generation. The USTER TESTER 4SX and 5<sup>21</sup> were used to evaluate the yarn unevenness  $CV_m$ , number of faults (*Thin* – 40%, *Thin* – 50%, *Thick* + 35%, *Thick* + 50%, *Neps* + 200%, and *Neps* + 280%), hairiness index  $H$  as well as *Trash count*, *Dust count* (testing condition: speed 400 m min<sup>-1</sup> and evaluation time 2 min, 5x).

The optical system implemented in USTER TESTER 4SX for assessment of yarn contamination detects particles only on accessible yarn surface relevant to the measured length in the range of size 100–1750 μm<sup>22</sup>. The ZWEIGLE G 567 was applied for analysis of the sum criteria of yarn hairiness  $S_{12}$  and  $S_3$  (testing condition: 100 m min<sup>-1</sup> and evaluation time 1 min, 5x). The INSTRON TESTER was taken for the measurement of the yarn tenacity  $F_{yarn}$  and yarn breaking elongation  $e_{yarn}$  (testing condition: length 500 mm, speed 500 m min<sup>-1</sup>, 50x). The number of strokes to yarn destruction was evaluated as yarn abrasion resistance by ZWEIGLE 552 (testing condition: all strokes, 50x) and the mass of separated abraded lint from a 1 km long yarn section of the wrapped yarns the Lawson-Hemphill constant tension transport instrument was used (testing condition: speed 100 m min<sup>-1</sup>, length 1 km, 1x).

### Woven fabric sample production and their basic qualitative assessment

The experimental woven fabric samples with a plain weave were produced using a SOMET rapier weaving machine with STÄUBLI electronic jacquard shedding mechanism. Weaving machine speed is 435 picks min<sup>-1</sup>. Reed working width of the machine is 148 cm. The fundamental parameters of the woven fabric construction are presented in Table 3. The selection of an industrial weaving machine, rather than a laboratory sampling weaving loom, was justified by the study's focus on processing waste materials. The difference in the weaving process dynamics is a crucial factor, as it can significantly influence fiber release in waste yarns. Although using a frame-shedding mechanism would have been a more cost-effective option, it would not have impacted the quality of the woven fabric samples. To ensure the process ability of the warp system, the warp was prepared from 100% Egyptian combed compact 2 × 6 tex two-ply cotton yarns with a ply twist level of 1100 m<sup>-1</sup> (S direction). Due to the poorer properties of waste yarns, a plain weave was chosen for the fabric construction. Plain weave is the weave with the most cohesive fabric structure. The warp system provides the supporting system from the point of view of production, cohesion and properties of the resulting fabric. In this fabric construction, the weft system with waste yarn is a filler. The float weaves in the fabric construction, we will achieve worse properties, due to the necessity of the weft position on the surface of the fabric at the place of floatation (non-interlacing place). The weft thread will be exposed to greater stress, which will lead to faster destruction of the fabric and its shorter lifetime compared to the construction of a fabric with a plain weave.

A standard qualitative assessment of the woven fabric was conducted. The density of ends  $D_e$  and density of picks  $D_p$  was measured in accordance with the EN 1049-2 standard using ten 100 mm × 100 mm samples. The areal mass  $m_{fabric}$  was determined following the ISO 12127 standard, also using ten 100 mm × 100 mm for ten samples. The mechanical properties, including fabric tensile force  $F_{warp}$ ,  $F_{weft}$  and elongation  $e_{warp}$ ,  $e_{weft}$ , were evaluated based on the ISO 13934 standard. These tests were performed using an INSTRON TESTER on ten samples in both main fabric directions, each with a length of 200 mm and testing speed of 100 m min<sup>-1</sup>.

### The methodology for the evaluation of woven fabric surface contamination

The potential alterations in fabric appearance caused by the presence of seed coat fragments were analyzed using image analysis and were inspired by techniques introduced in<sup>22–24</sup>. The appropriate magnification and calibration of the scanned woven fabric images were selected to accurately capture and describe the smallest details, particularly the size of impurities. The images were scanned using an upper lighting system and a minimally contrasting background to effectively distinguish dark-colored impurities, primarily seed coat fragments, from the fabric structure while minimizing the influence of dark pores between the yarns. The scanning was performed on the fabric in its gray state after the relaxation process. To ensure reliable evaluation, the captured images needed to include a sufficient length of weft yarn, and the number of detected impurities on the fabric surface had to be statistically adequate for minimal sampling in the data processing. The length of the weft thread on the surface of the fabric can be expressed based on the definition of the spatial geometry of the fabric. The spatial geometry can be described based on the longitudinal and transverse cross-sections of the fabric. From the waviness of the weft and warp threads and the thread distances, the length of the threads on the surface of the fabric can be expressed. A description of the spatial geometry and fabric cross-sections of the studied fabrics is given in Chap. 3. A total of 200 microscopic images were captured at a resolution (image width  $a = 2880$  px, image height  $b = 2048$  px), with a calibration of  $c = 7.98 \mu\text{m px}^{-1}$  to ensure the correct description of the smallest particle on the image – dust impurity. Half of the images were taken from the front and half from the back of the woven fabric to identify and describe the nature of the visible impurities from the area of fabric

Fiber blend	CO waste 100%	CO waste/CO 75%/25%	CO waste/CO 50%/50%	CO waste/CO 25%/75%	CO 100%
Used cleaning channel	A, C, W	A, C, W	A, C, W	A, C, W	A, C, W
End count $T_e$ [tex]	6 × 2				
Pick count $T_p$ [tex]	29.50				
Density of ends $D_e$ [cm <sup>-1</sup> ]	30				
Density of picks $D_p$ [cm <sup>-1</sup> ]	22				

**Table 3.** Construction parameters of woven fabric samples.

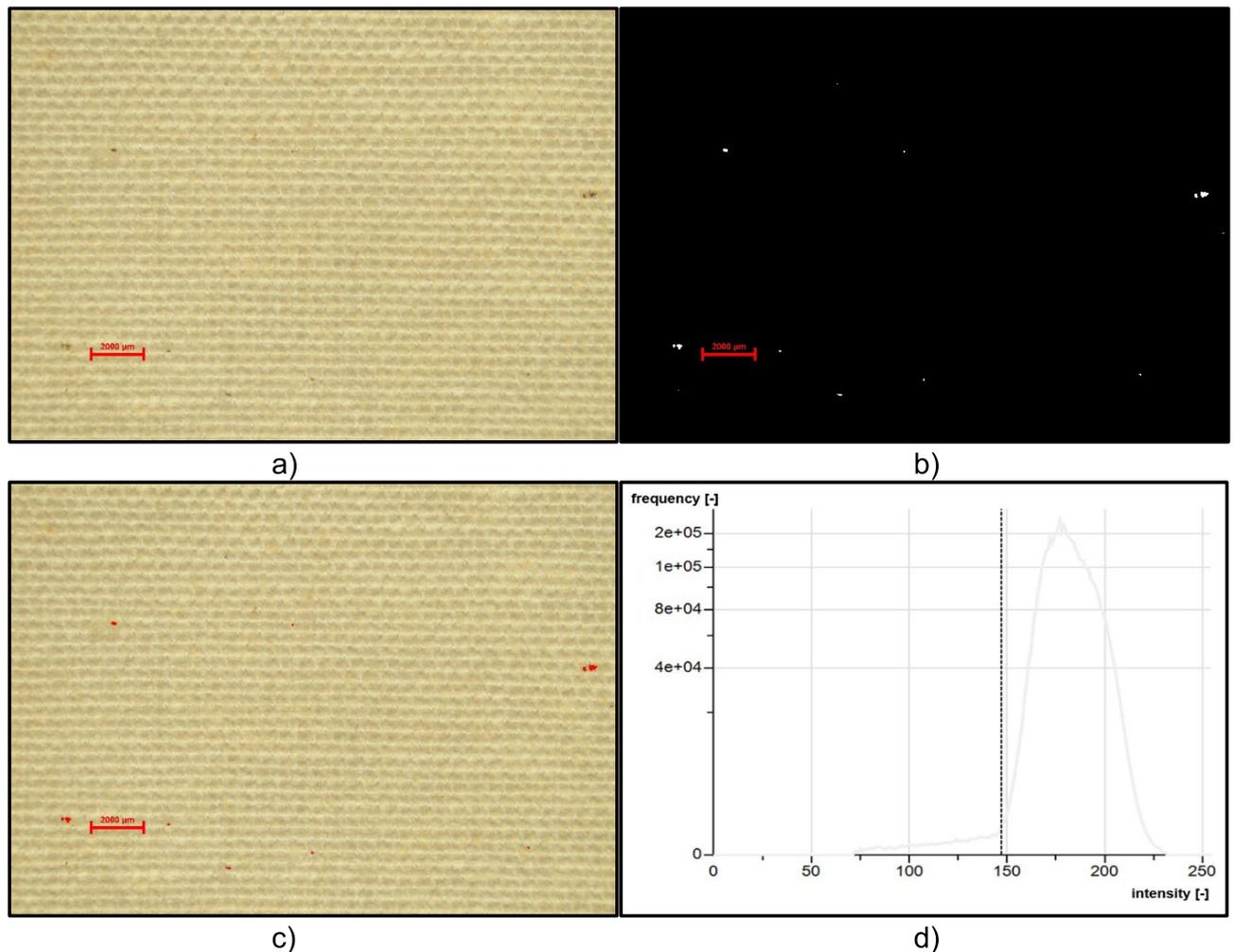
produced from 6.6 km of weft yarn. The chosen condition of woven sample preparation (same warp system and same construction for all fabric samples  $D_e, D_p$ ) and the same setting for fabric scanning (resolution  $a \times b$ , calibration  $c$ , and number of images) for the evaluation of fabric contamination ensures that the same area of fabric for each sample was evaluated. The high quality of the used warp system provides minimal contamination by dust or trash particles. In other words, the contribution of the warp system to fabric contamination can be neglected. Based on the presumption that the waviness of the weft is minimal, the rough estimation of weft yarn length can be realized. When the size of the image and number of pics  $D_p$  are taken into consideration, the length of weft yarn in all 200 images for each sample is about 0.165 km.

The character of the scanned images enables the identification of an appropriate threshold for converting color images into a gray image and then into a binary form based on the bottom end of the image histogram. The image processing method is illustrated in Fig. 1, showing a woven fabric sample in plain weave produced with the 29.5 tex 100% CO waste yarn spun with W cleaning channel. The appearance of the fabrics is primarily influenced by the presence of seed coat fragments and fiber neps, as these impurities can cause visual defects after dyeing. In this study, the dark color impurities caused by plant fragments and seed coat fragments are taken into account. To quantify and qualify the character of impurities, both object and field features were analyzed to determine the contamination of the fabric surface.

The detected objects' area  $A_{object}$  was measured. The presumption of equivalence among the area of objects  $A_{object}$  and circle  $A_{circle}$  is used to calculate the equivalent diameter  $d$ , see the Eq. (1).

$$A_{object} = A_{circle} = \frac{\pi d^2}{4} \quad (1)$$

Additionally, minimum and maximum Ferret's diameters  $ferret_{min}, ferret_{max}$  were assessed, as seed coat fragments and dust particles exhibit convex character. The USTER AFIS PRO 2 classification sorts out impurities detected on yarn surfaces into two categories (dust and trash) based on their size, where the dividing boundary is 0.5 mm<sup>20</sup>. It is not clear what type of size specification is used, whether the equivalent diameter  $d$  or Feret's diameter



**Fig. 1.** Example of processing of woven structures in plain weave. (a) Color image. (b) Binary image—separated impurities (c) overlaid image (d) grayscale image histogram.

( $ferret_{min}$  or  $ferret_{max}$ ). Following the recommendations for the classification of yarn impurities<sup>20</sup>, the detected particles were categorized on the basis of the equivalent diameter  $d$  (criterion 1) and the maximum Feret's diameter  $ferret_{max}$  (criterion 2) with the limit boundary size 0.5 mm.

The specifications of whether the impurity was dust or trash were realized with respect to equations (criterion 1: Eq. 3a, b) and (criterion 2: Eq. 4a, b), and the number of impurities (dust, trash) and their shape character were evaluated.

$$\begin{aligned} n_{dust} &= |\{d \mid d = d_{dust} \leq 0.5\text{mm}, i = 1, \dots, k\}| \\ n_{trash} &= |\{d \mid d = d_{trash} > 0.5\text{mm}, j = 1, \dots, l\}| \end{aligned} \quad (2a,b)$$

$$\begin{aligned} n_{dust} &= |\{feret_{max} \mid feret_{max} = feret_{max\ dust} \leq 0.5\text{mm}, i = 1, \dots, k\}| \\ n_{trash} &= |\{feret_{max} \mid feret_{max} = feret_{max\ trash} > 0.5\text{mm}, j = 1, \dots, l\}| \end{aligned} \quad (3a,b)$$

Various parameters can be used to describe the impurity shape character. The ovality or circularity, as well as the shape factor, can be used. To be able to explain how the detected object varies from the circle, the shape factor  $q_{object}$  is selected. Its definition is given by the Eq. (3).

$$q_{object} = \frac{p_{object}}{p_{circle}} - 1 = \frac{p_{object}}{\pi d_e} - 1 \quad (4)$$

In addition, the qualitative shape parameter - elongation  $e_{object}$  is also analyzed as the portion of minimal and maximal Feret's diameter to get an idea about the proportion of detected objects, see Eq. (4).

$$e_{object} = \frac{feret_{max}}{feret_{min}} \quad (5)$$

The *binary portion* is calculated as a field feature to give a complex idea of the impurity's effect on the fabric's visual quality. The indices  $i$  and  $j$  are utilised to diversify the dust and trash particles. The index  $i$  ranges from 1 to  $k$ , where  $k$  denotes the total number of dust particles detected. In a similar manner, the index  $j$  ranges from 1 to  $l$ , where  $l$  corresponds to the total number of detected trash particles. The definition of the *binary portion* is based on the area fraction of all dust particles  $A_{dust}$  and all trash particles  $A_{trash}$  divided by the whole area of the sample  $A_{measured}$ , see Eq. (5a). The whole area of the sample  $A_{measured}$  is given by image resolution  $a \times b$  and calibration  $c$ . The partial binary portion for dust and trash (*binary portion<sub>dust</sub>*, *binary portion<sub>trash</sub>*) is then calculated by (6b, c).

$$binary\ portion = \frac{A_{dust} + A_{trash}}{A_{measured}} = \frac{\sum_{i=1}^k A_i + \sum_{j=1}^l A_j}{abc^2} \quad (6a)$$

$$binary\ portion_{dust} = \frac{A_{dust}}{A_{measured}} = \frac{\sum_{i=1}^k A_i}{abc^2} \quad (6b)$$

$$binary\ portion_{trash} = \frac{A_{trash}}{A_{measured}} = \frac{\sum_{j=1}^l A_j}{abc^2} \quad (6c)$$

## Statistical data processing

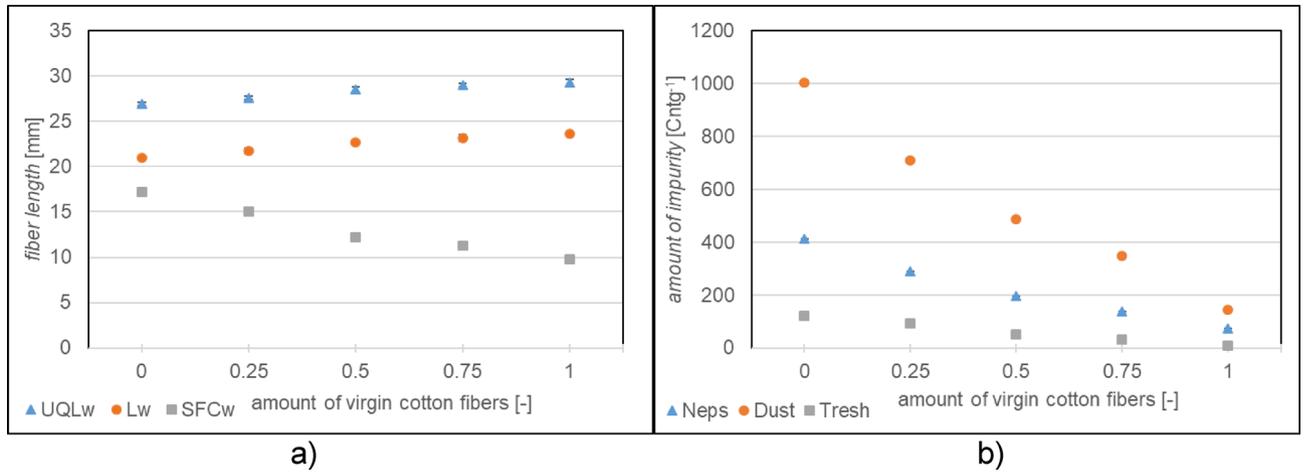
All experimental data underwent statistical processing, including verification of normality and homogeneity<sup>25</sup>. The appropriate methodologies (typically the exponential transformation of data - for non-Gaussian distribution, excluding outliers - if detected) were applied to determine key statistical parameters, including mean, standard deviation, coefficient of variation, and a 95% confidence interval. In most cases of qualitative assessment of impurities (their size and shape parameters), the most suitable exponential data distribution was detected. The validity of the data transformation has been verified by means of the likelihood function. Only for the characteristics where the small data set is obtained (set of ends  $D_p$ , set of picks  $D_p$ , fabric mass  $m_{fabric}$  and mechanical parameters of fabric  $F_{warp}$ ,  $F_{weft}$ ,  $e_{warp}$  and  $e_{weft}$ ), the Horn's principle of statistical parameters, including mean, standard deviation, variation coefficient, and 95% confidence bounds, is used<sup>25</sup>.

## Results and discussion

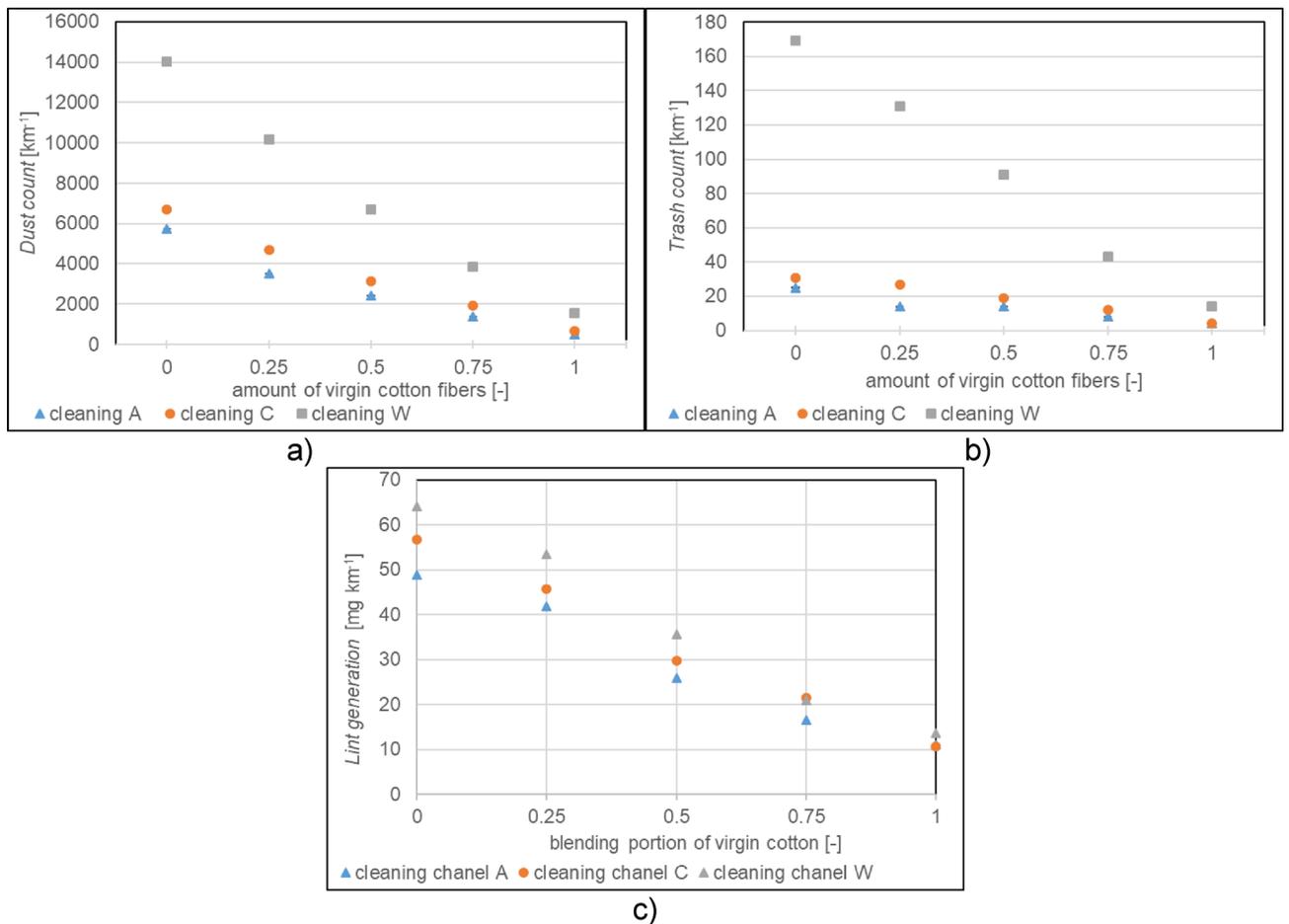
### Impact of cotton waste portion and cleaning method on open-end rotor yarn quality

The previous study<sup>18</sup> examined the effect of different blending portions of cotton waste processed the same way by Rieter R 37 open-end spinning machine by adopting the three types of cleaning channels (A, C, W). As an illustration of the difference in quality between fiber blends, Fig. 2 shows a graphical comparison for selected fiber parameters (fiber upper quantile  $UQL_w$  length, mean length  $L_w$ , and short fiber content  $SFC_w$ , number of impurities *Neps*, *Dust*, and *Trash* in slivers), including the 95% confidence intervals. It is clearly visible that fiber length (fiber upper quantile  $UQL_w$  length, mean length  $L_w$ ) slightly increases as the amount of cotton waste in slivers decreases. Short fiber content  $SFC_w$  and impurities (*Neps*, *Dust*, *Trash*) decrease as cotton waste in slivers decreases. Due to the data character, the confidence bounds are too narrow and, in some cases, less visible.

To demonstrate the differences among open-end rotor yarns spun by various cleaning channels (A, C, W), the comparison for impurity counts (*Trash count*, *Dust count*) in yarns together with *Lint generation* during yarn-on-yarn abrasion is shown in Fig. 3. The mean together with the 95% confidence intervals of *Trash count*



**Fig. 2.** The quality of fiber blends used for the production of open-end rotor weft yarns (a) fiber length (b) amount of impurity.



**Fig. 3.** The contamination of open-end rotor yarns and amount of lint generation<sup>18</sup>. (a) Dust count (b) Trash count (c) Lint generation.

and *Dust count* are presented in the figure to get a complex idea about their variability. However, they are very narrow and less visible due to a sufficiently high number of measured values (one value for each 1 cm of the measured 5 × 1 km of yarn). *Lint generation* was measured only for 1 km of yarn, and therefore, the graphical interpretation of the trend behavior of various yarns is based on one experimental value for each sample.

The deterioration in fiber quality in terms of length ( $UQL_w, L_w$ ), short fiber content  $SFC_w$  and amount of impurities with increasing cotton waste content in the sliver is also reflected in the amount of yarn impurities (*Trash count, Dust count*). Higher release of fibers, fiber fragments, and/ or seed coat fragments in terms of *Lint generation* are found in yarns spun with a higher portion of cotton waste, even though a higher twist has been used. The lower degree of fiber arrangement in these yarns and the lower fiber length characteristics ( $UQL_w, L_w$ ) with a significantly higher short fiber content  $SFC_w$  in slivers are probably the main reasons. The findings confirmed that it is possible to produce 29.5 tex rotor-spun yarns from a blend of recycled cotton fibers, with or without virgin cotton, by carefully selecting the appropriate spinning strategy and twist level. Although the innovative cleaning method W resulted in some deterioration of specific yarn quality parameters (*Trash count, Dust count*), the overall quality remained within the acceptable range according to USTER STATISTICS<sup>26</sup> valid for the year 2020.

Moreover, the study<sup>18</sup> showed that yarns composed entirely of recycled cotton could achieve quality levels comparable to those made from virgin fibers when the cleaning and spinning parameters were properly adjusted.

### Impact of cotton waste portion and cleaning method on standard fabric characteristics

Building on these insights, the next phase of research was realized. The impact of blending portion of cotton waste, resulting in various portions of yarn contamination by dust and trash particles was analyzed on woven fabric in plain weave having the same construction parameters and warp threads system.

The open-end rotor yarns with identical 29.5 tex counts exhibited similar overall quality, with differences primarily observed in the number of faults and impurity contamination mainly in the case of yarn spun with cleaning channel W. Consequently, when processed into woven fabrics as weft yarns under the same construction parameters, plain weave, using identical weaving machines with the same setting only minor variations in fabric properties were expected, largely influenced by yarn quality.

The mean and 95% confidence boundaries of experimental data for selected fabric parameters are shown in Table 4. The results verified this expectation in terms of fabric mass, density of ends  $D_e$ , and density of pics  $D_p$ . The diversities are mostly covered by confidence bounds overlapping. The mechanical parameters ( $F_{fabric\ warp}, F_{fabric\ weft}, e_{fabric\ warp}, e_{fabric\ weft}$ ) in both main directions are also comparable from the point of view of a blend of cotton waste (from 100 to 0% of cotton waste) as well as the cleaning channel (A, C, W) used. The slight increase of relative force of  $F_{fabric\ weft}$  in connection with the weft yarn spun from 100% virgin cotton is visible but still statistically insignificant due to overlaps of confidence bounds.

To demonstrate the appearance of the fabric surface influenced by the cotton waste yarn in the weft system, the planar view and cross-sections in both main directions of the fabric are provided. The planar view was taken as a detail from the fabric woven from the weft yarn 29.5 tex 100% CO waste spun by cleaning channel W) see Fig. 4.

The longitudinal and transverse cross-sections of the fabric prepared by the technique of soft cross-section are presented in Fig. 5a, b. The cross-sections of the fabric are made from the fabric presented in Fig. 4. As can be seen from the cross-sections, the spatial geometry of the fabric is defined by an uneven structure. The warp system is maximally wavy and wraps the weft yarns, see Fig. 5a. The waviness of the weft waste yarns is in a straightened shape with almost zero waviness, see Fig. 5b. The weft waste yarns, in this case, form a filling. The weft waste yarns are protected on the fabric surface of the warp yarns. The length of the weft yarns on the surface of the fabric are given by the distance between two warp threads. The length between two warp threads defines the thread distance. The geometric relationship between the thread distance and the thread density can be defined based on the reciprocal value, where the thread distance is equal to the reciprocal value of the thread density.

### Impact of cotton waste portion and cleaning method on contamination of fabric surface

To determine whether yarn contamination affects fabric contamination, it is essential to consider that some impurities are released during each production phase. As the yarn is rewound and processed into fabric, it comes into contact with multiple guiding elements, where friction causes the detachment of loosely bound fiber segments as well as the loosening of impurities not firmly fixed to the yarn surface. In addition, the dynamic nature of the weaving process results in the removal of dust particles from the yarn surface and the breaking of impurities due to its fragility. Consequently, the number of detected impurities on the fabric surface is expected to be lower, as some remain hidden within the fabric structure due to the arrangement of yarns, making them invisible from both the face and reverse sides.

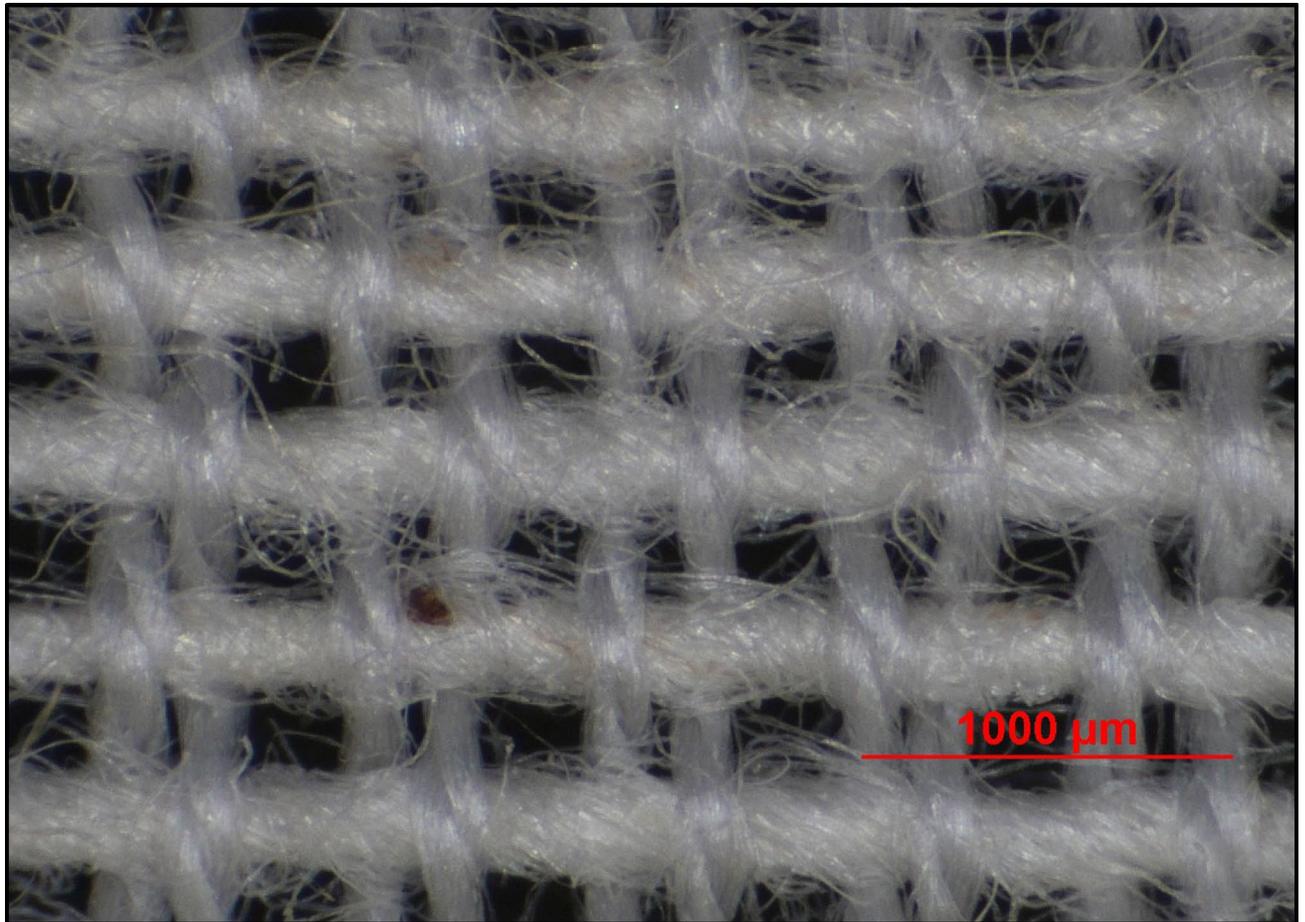
The higher release of fibers and fiber fragments of segments of plant impurities from the cotton waste yarn is partly confirmed by the evaluation of *Lint generation* during yarn-on-yarn abrasion, see Fig. 3c. More frequent cleaning of all guiding parts of the weft yarns and the beating area of the weaving machine was required during fabric production. This was especially necessary when processing weft yarns with a higher cotton waste content and those spun using cleaning channel W, see Fig. 6.

Industrial weaving mills set up suction equipment when processing yarns with greater or lesser dustiness. Greater dustiness of yarns automatically activates more frequent suction than yarns with less dustiness. Suction of dust from yarns is an important production factor in relation to the resulting quality of the fabric in general, not only when processing waste materials. Furthermore, in the case of greater dustiness, industrial production sets up cleaning of weaving machines after weaving, where all impurities arising during weaving are sucked off. It is known from practice that possible contamination during weaving comes from the primary raw material that is woven.

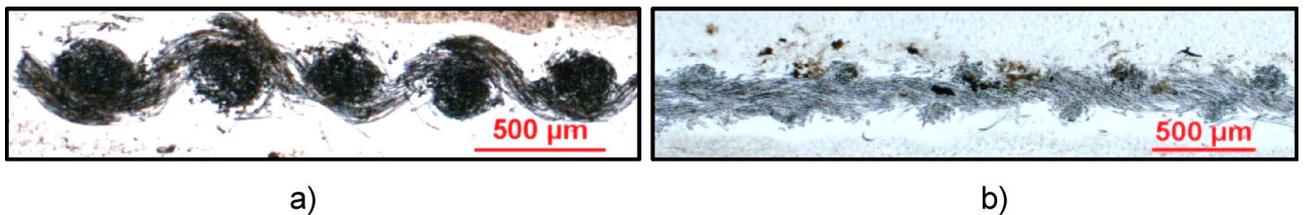
An example of a woven fabric planar view of potentially the most contaminated (the weft yarn 29.5 tex 100% CO waste spun by cleaning channel W) and the minimally contaminated fabrics (the weft yarn 29.5 tex 100% CO spun by cleaning channel A) is shown on Fig. 7.

Fibre blend	100% CO waste			25% CO/75% CO waste			50% CO/50% CO waste			75% CO/25% CO waste			100% CO		
	A	C	W	A	C	W	A	C	W	A	C	W	A	C	W
Cleaning channel	29.5														
$T_p$ [tex]	932														
$Z$ [m <sup>-1</sup> ]	901														
$m$ [gm <sup>-2</sup> ]	985	106.0	105.5	102.5	104.5	103.5	103.5	105.0	102.5	102.5	103.5	100.5	103.5	102.5	102.5
	(104.0; 105.0)	(105.0; 107.0)	(105.0; 106.0)	(100.9; 104.1)	(104.0; 105.0)	(101.9; 105.1)	(100.9; 104.1)	(104.0; 106.0)	(100.9; 104.1)	(100.9; 104.1)	(103.0; 104.0)	(103.0; 104.0)	(103.0; 104.0)	(100.0; 101.0)	(102.0; 104.1)
$D_d$ [cm <sup>-1</sup> ]	30.5	30.0	31.0	31.0	30.0	31.5	31.0	30.0	31.5	31.5	30.0	31.0	30.0	31.0	31.0
	(30.0; 31.0)	(30.0; 30.0)	(31.0; 31.0)	(31.0; 31.0)	(30.0; 30.0)	(31.0; 32.0)	(31.0; 31.0)	(30.0; 30.0)	(31.0; 32.0)	(31.0; 32.0)	(30.0; 30.0)	(31.0; 31.0)	(30.0; 30.0)	(31.0; 32.0)	(30.0; 31.0)
$D_p$ [cm <sup>-1</sup> ]	23.0	21.5	23.0	22.5	21.5	22.5	22.5	22.0	22.5	22.5	22.0	22.0	22.0	22.0	22.5
	(23.0; 23.0)	(21.0; 22.0)	(23.0; 23.0)	(22.0; 23.0)	(21.0; 22.0)	(22.0; 23.0)	(22.0; 23.0)	(22.0; 22.0)	(22.0; 22.0)	(22.0; 23.0)	(22.0; 23.0)	(22.0; 22.0)	(22.0; 22.0)	(22.0; 23.0)	(22.0; 23.0)
$F_{fabric\ warp}$ [N/5 cm]	363.8	377.4	368.0	373.8	377.5	376.3	358.6	384.3	368.2	378.4	369.9	347.6	347.6	347.6	361.5
	(338.3; 389.4)	(358.7; 396.0)	(331.4; 404.6)	(365.9; 381.6)	(351.4; 403.7)	(357.7; 394.9)	(344.9; 372.3)	(379.8; 388.8)	(339.5; 396.8)	(353.1; 403.7)	(334.9; 404.8)	(313.3; 381.9)	(322.3; 372.8)	(350.4; 382.9)	(338.0; 384.9)
$F_{fabric\ weft}$ [N/5 cm]	246.8	259.7	231.1	252.9	257.8	238.8	265.5	274.0	261.1	290.9	293.1	274.8	296.1	305.3	295.1
	(232.8; 260.9)	(243.8; 275.5)	(226.4; 235.9)	(249.7; 256.2)	(248.1; 267.5)	(224.8; 252.8)	(250.0; 281.0)	(262.2; 285.8)	(248.4; 273.8)	(282.6; 299.1)	(268.1; 318.0)	(261.9; 287.7)	(284.6; 307.7)	(287.6; 323.1)	(289.2; 301.0)
$e_{fabric\ warp}$ [%]	16.7	18.7	16.3	16.7	17.8	16.8	17.1	19.2	17.5	16.9	19.2	15.9	15.5	17.6	15.9
	(15.9; 17.4)	(16.8; 20.6)	(15.8; 16.8)	(16.3; 17.0)	(17.1; 18.5)	(16.6; 17.1)	(16.8; 17.4)	(19.1; 19.4)	(17.2; 17.9)	(16.1; 17.6)	(17.8; 20.6)	(14.9; 16.8)	(15.0; 16.0)	(17.4; 17.8)	(15.2; 16.6)
$e_{fabric\ weft}$ [%]	6.3	6.3	5.9	6.2	6.6	6.3	6.3	7.0	6.3	6.4	6.7	6.4	5.8	6.6	6.3
	(5.8; 6.8)	(6.2; 6.5)	(5.5; 6.2)	(5.6; 6.9)	(6.3; 6.9)	(6.0; 6.7)	(5.9; 6.7)	(6.4; 7.7)	(5.8; 6.8)	(6.0; 6.7)	(6.6; 6.8)	(6.1; 6.8)	(5.2; 6.5)	(6.5; 6.6)	(5.9; 6.6)

**Table 4.** The selected fabric parameters.



**Fig. 4.** The appearance of the fabric surface influenced by the weft yarn 29.5 tex 100% CO waste spun by cleaning channel W (fabric detail).



**Fig. 5.** The woven fabric cross-section with weft yarn 29.5 tex 100% CO waste spun by cleaning channel W (a) the longitudinal cross-section - the binding wave is warp thread (b) the transverse cross-sections - the binding wave is weft thread.

Objects detected on the woven fabric surface were classified as dust particles if their equivalent diameter  $d$  or maximum Feret's diameter  $feret_{max}$  was less than 0.5 mm (criterion 1:  $d = d_{dust} \leq 0.5$  mm; criterion 2:  $feret_{max} \leq 0.5$  mm), see equations (3a and 3a). Particles larger than 0.5 mm in terms of  $d$  or  $feret_{max}$  (criterion 1:  $d_e = d_{trash} > 0.5$  mm; criterion 2:  $feret_{max} > 0.5$  mm) were classified as trash impurities, see equations (3b and 3b). The graphical comparison of total numbers of dust  $n_{dust}$  is shown in Fig. 8a, and total number of trash particles  $n_{trash}$  is shown in Fig. 8b for all woven fabric samples.

The legend provides a description of the cleaning channel and the criteria used to categorize dust and trash particles. It is visible that the selection of criteria for the classification of impurities into dust and trash categories is very important and leads to totally different results in values, but the trends remain the same. Using criterion 1 ( $d = d_{trash} > 0.5$  mm), the number of particles marked as trash is significantly lower than using criterion 2 ( $feret_{max} > 0.5$  mm). The innovative cleaning channel W ensures that shorter fibers are formed in the yarn structure, the fiber yield is higher, but the contamination of the yarn by trash and dust particles is higher. This also results in a higher number of impurities detected on the fabric surface if the weft yarn spun by cleaning channel W is used.

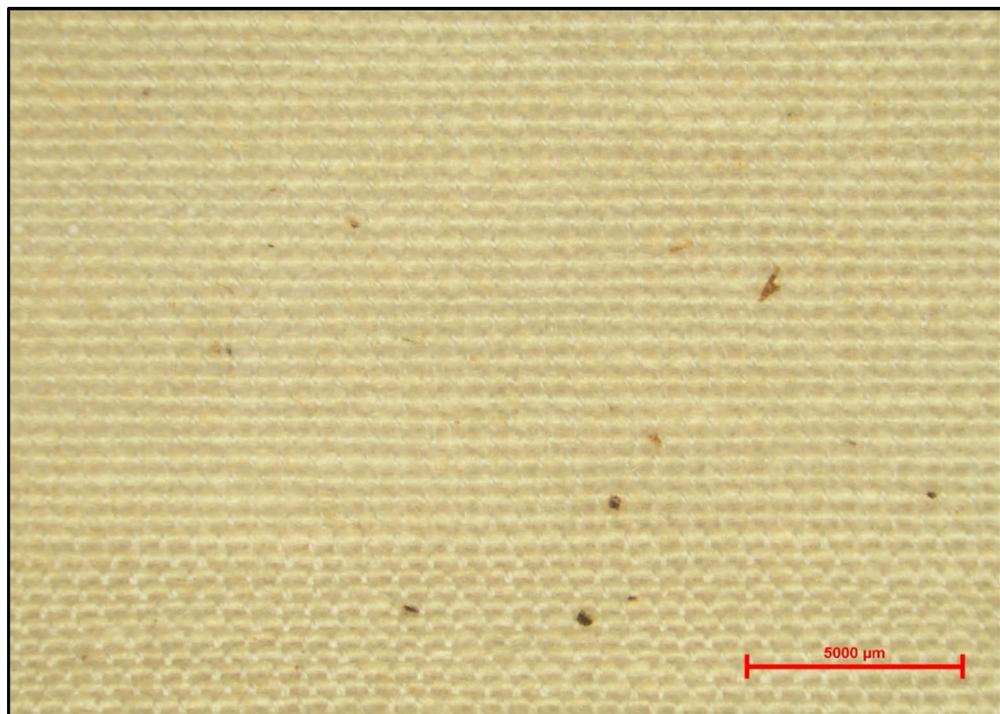


**Fig. 6.** Deposit of fiber fragments and impurities released from weft yarns during weaving. **(a)** unwinding area of weft yarn **(b)** beating area of fabric.

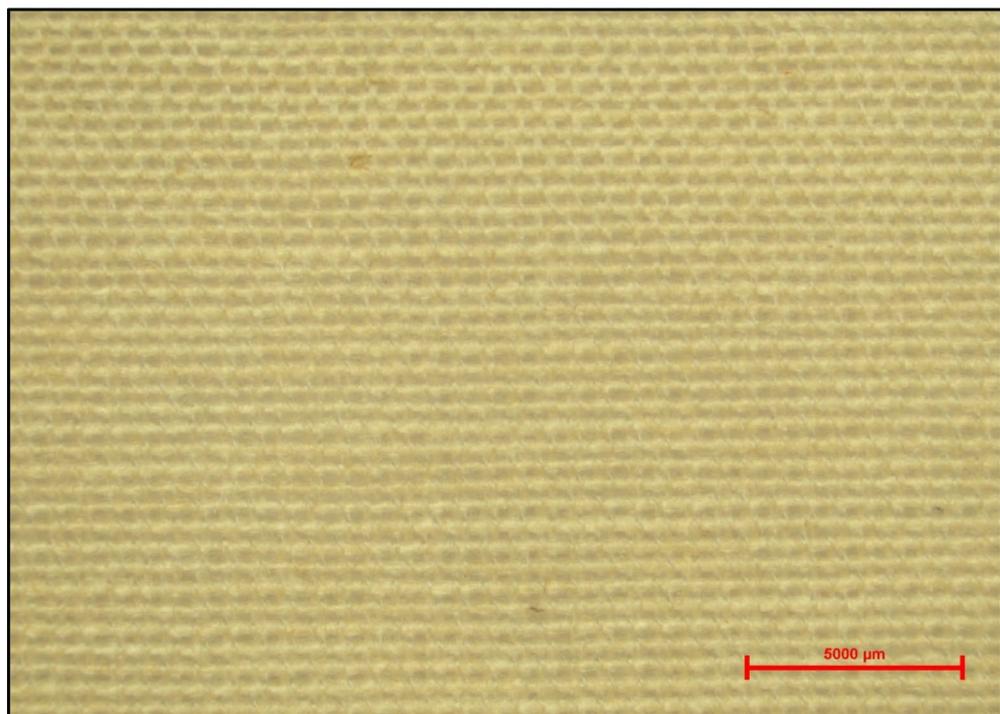
The comparison of yarn and fabric contamination in terms of the number of detected particles is not provided. Building up the serious semi-theoretical estimation of a number of contaminants based on the data of yarn contamination is problematic mainly because of the facts mentioned below:

- *Various conditions for yarn and fabric samples contamination evaluation setup and sensitivity.* The contamination of the weft yarn in terms *Dust count*, *Trash count* realized by USTER TESTER 5 evaluates only on  $\frac{1}{2}$  of the yarn surface relevant to the measured length, and the sensor detects particle size in the range of 100–1750  $\mu\text{m}$ <sup>21</sup>. The calibration 7.98  $\mu\text{m px}^{-1}$  used for scanning fabric images was selected as more sensitive to detect smaller fragments and give more relevant information for potential needs of correction of the final fabric treatment process. The majority of detected dust particles on fabric surface are smaller than 100  $\mu\text{m}$  in terms of  $feret_{max\ dust}$ . Figure 9 shows an example of histograms of dust particles detected on fabric surface with the cumulative function. Moreover, the categories relevant to dust particles having  $feret_{max\ dust} \leq 100 \mu\text{m}$  are highlighted in red. Hence, the number of detected particles for a 1 km yarn length is used only as an indicator of yarn contamination, not as a value for estimating the fabric contamination values.
- *An expression of the length of yarn in the analyzed fabric and its surface with respect to the fabric structure.* The problematic part is the expression of the surface of the yarn, which is taken into account for the detection of impurities on yarn itself and on the fabric surface woven from these yarns. To calculate the length of the weft waste yarn on the surface of the fabric, a length calculation based on the structure and geometry of the fabric can be used. As mentioned above, the length of the weft yarn on the surface of the fabric is given by the distance between two warp threads. The length between two warp threads defines the thread distance. The geometric relationship between the thread distance and the thread density can be defined based on the reciprocal value, where the thread distance is equal to the reciprocal value of the thread density.
- *Transformation and loss of impurities during weaving.* Some of the impurities may change their character due to their fragility. Hypothetically, a single trash particle decomposes into several smaller particles due to friction and mechanical stress during weaving, and next, it is detected as a sequence of dust on the fabric surface. A further complication is that some of these newly created pieces can become detached. It is impossible to easily obtain information on the amount of particles that are shed during weaving, which requires a specific experiment.

The following analysis is based on the data, where only criterion 2 for defining dust, respectively, trash particles, is used. The assumptions about size parameters are based on previous research and long-term experience. Only small variations in the size parameters of the dust and trash contaminants are to be expected when different amounts of cotton waste are used since the contaminants have the same origin. Ferret's diameters may be more suitable, as larger contaminants tend to have a convex shape character. The size and shape characteristics of contaminants in different weft yarns produced using the three cleaning channels (A, C, W) remain similar. The obtained results are presented in Fig. 10, where the mean values together with 95% confidence intervals are presented. The results are in good accordance with the assumptions. Values of equivalent diameter and Ferret's diameters significantly differ for both types of contaminants (dust and trash particles). The equivalent diameter ( $d_{dust}$ ,  $d_{trash}$ ) is significantly lower than the maximal Ferret's diameter ( $feret_{max\ dust}$ ,  $feret_{max\ trash}$ ). It can be concluded that the size of dust particles described by the equivalent diameter or Ferret's diameters tends to decrease as the amount of cotton waste in used weft yarns in woven fabric decreases. On the other hand, the diversity is also connected with the precision of the measurement; the lowest detail in the image is given by using



a)

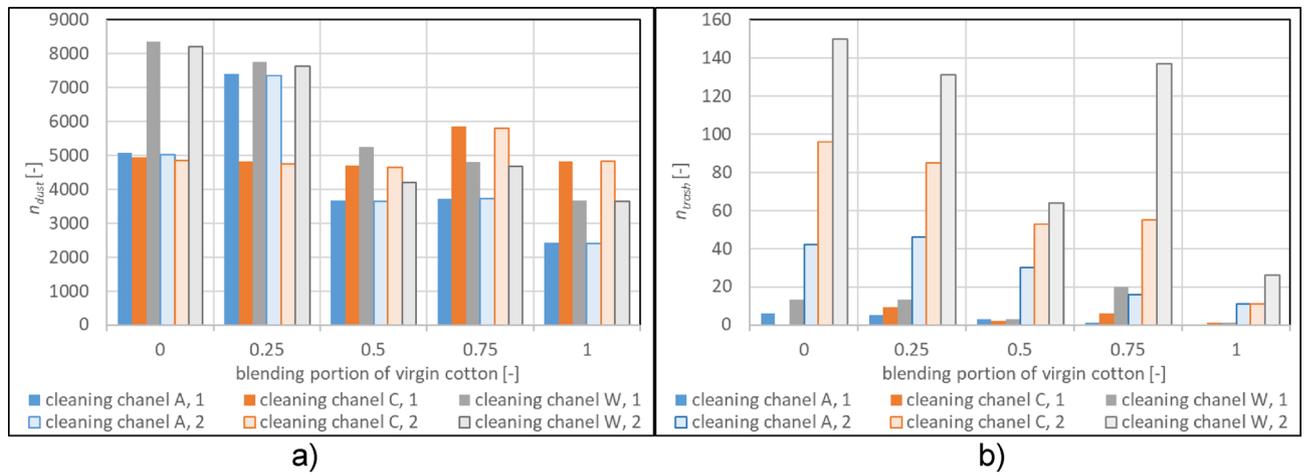


b)

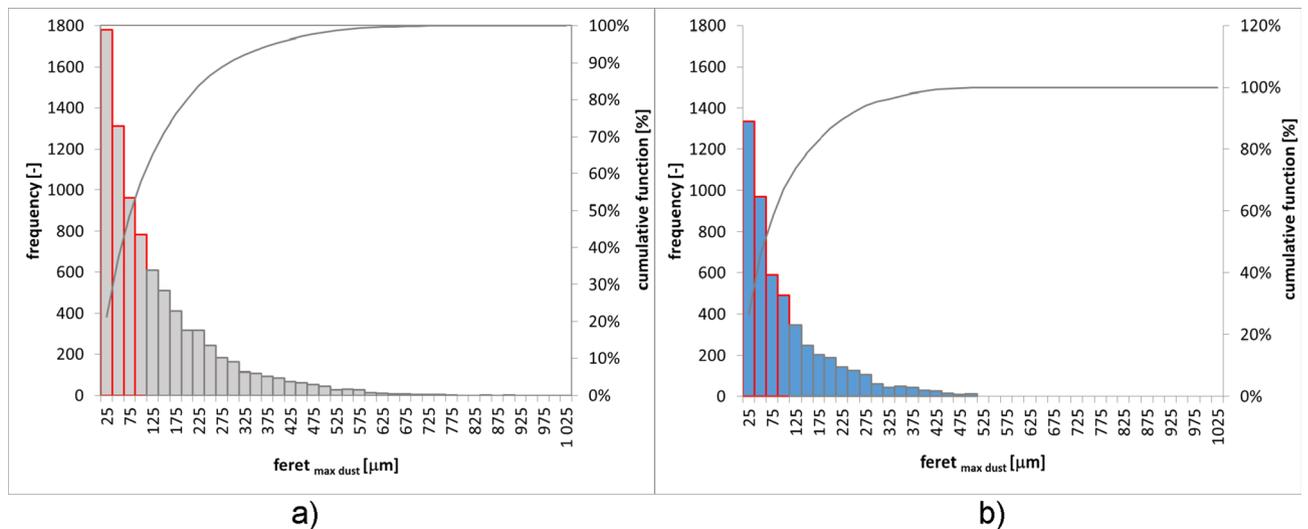
**Fig. 7.** An example of a woven fabric views (a) weft yarn 29.5 tex 100% CO waste spun by cleaning channel W (b) weft yarn 29.5 tex 100% CO spun by cleaning channel A.

calibration  $7 \mu\text{m px}^{-1}$ . In the case of trash particles, the size characteristics are not affected by the type of cleaning channel used, nor by the ratio of cotton waste in used weft yarns in the woven fabric.

A comparison of contaminant shape characteristics in terms of mean and 95% confidence intervals ( $q_{dust}$ ,  $q_{trash}$ ,  $e_{dust}$ ,  $e_{trash}$ ) is shown in Fig. 11. The experimental data confirmed that impurity shapes in terms of shape factor and elongation vary by category, with higher values observed for trash particles. The contaminants were generally non-circular and slightly elongated. The shape factor for dust was  $q_{dust} = 0.14$ , while for trash it was



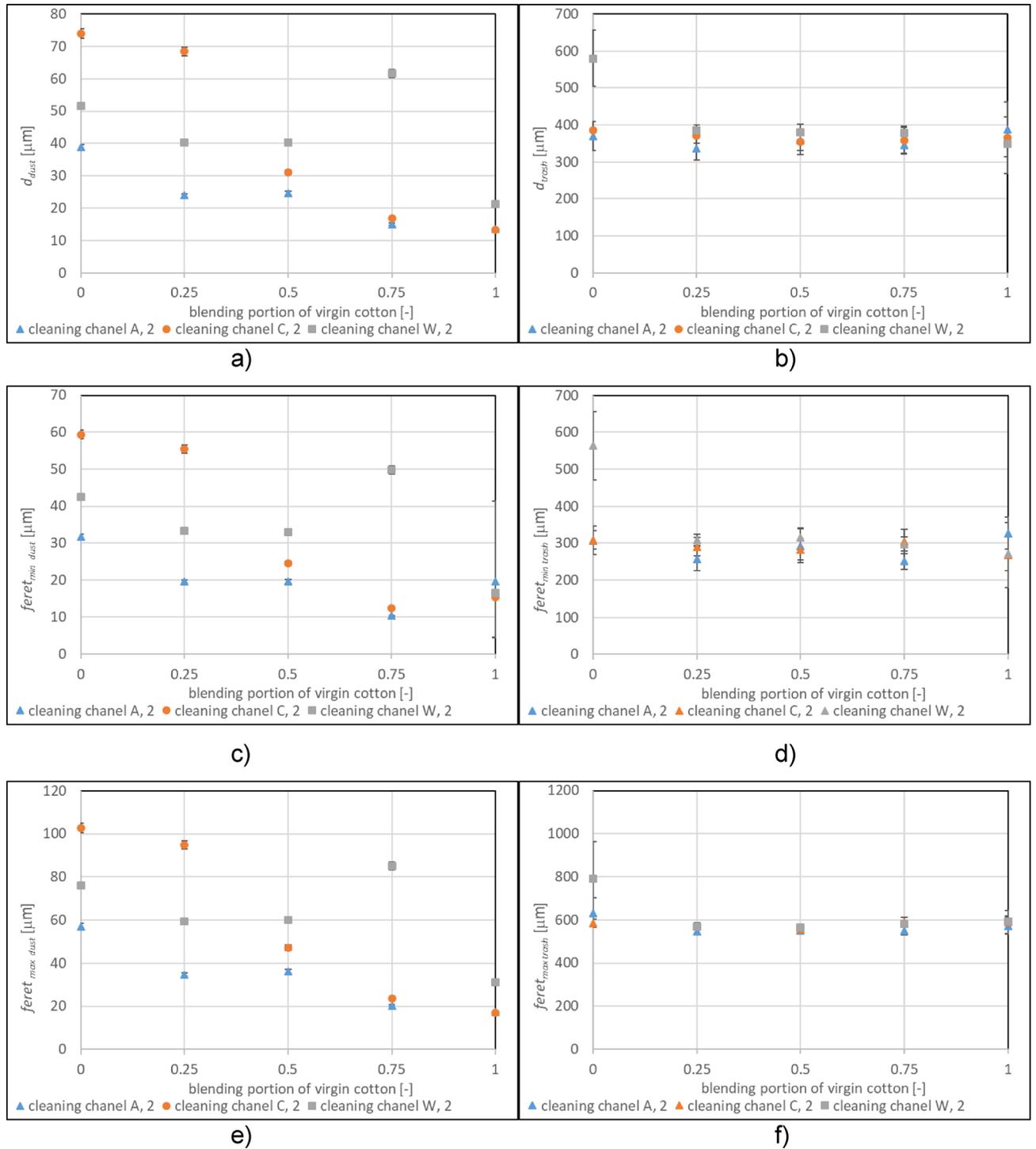
**Fig. 8.** Comparison of the number of dust and trash particles by using two criteria for categorization (a) number of dust particles  $n_{dust}$  (b) number of trash particles  $n_{trash}$ .



**Fig. 9.** Histogram and cumulative function of dust particles for fabric (a) weft yarn 29.5 tex 100% CO waste spun by cleaning channel W (b) weft yarn 29.5 tex 100% CO spun by cleaning channel A.

$q_{trash} = 0.57$ . Similarly, the elongation of dust particles was  $e_{dust} = 1.5$ , whereas for trash particles it was  $e_{trash} = 1.95$ . Neither the cleaning channel nor the cotton waste content in the weft yarns significantly affected these shape characteristics, as indicated by the overlapping confidence intervals.

The binary portion for all detected particles is calculated, as well as the binary portion separately for trash and dust particles in respect to the definition by Eq. 5c. The categorization of particles is done in accordance with the criterion 2. The graphical comparison is shown in Fig. 12, where the mean, together with the 95% confidence intervals, is presented. In view of the results presented earlier, it can be assumed that the differences between the binary proportions will be very small and statistically insignificant due to overlapping confidence intervals. However, they may provide information on trends of the different analyzed types of woven fabric made of various weft yarns from the point of view of the used blending ratio of cotton waste and the cleaning channel applied. The results of the yarn analysis proved that the amount of dust and trash particles decreases as the cotton waste decreases and moreover, the yarn spun by cleaning channel W has the largest amount of impurities. Thus, it can be expected that the trend of the binary portion will also be affected. The results indicate that the binary proportion of all contaminants tends to decrease as the cotton waste content in the weft yarns decreases. Additionally, the lowest binary proportions were observed when using cleaning channel A, followed by channels C and W. Interestingly, the contribution to the binary portion given by dust particles is comparable to that of trash particles. Previous research has shown that the smaller impurities have a smaller impact on the visual quality of the woven fabric and are more likely to be removed during pretreatment. However, they are important in terms of bath contamination and the need for filter cleaning in water-based processes. Therefore, when optimizing the



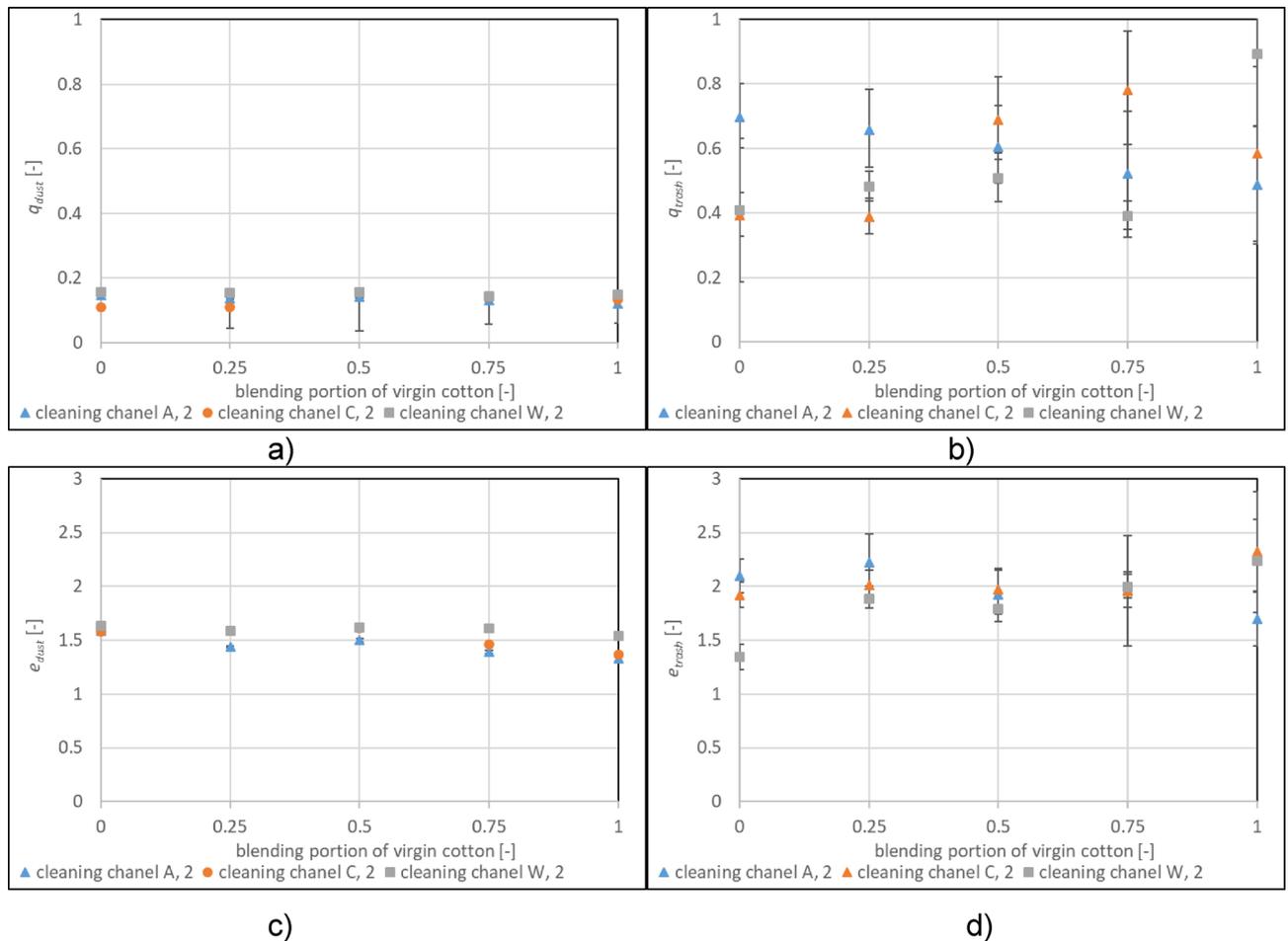
**Fig. 10.** Comparison of the size impurity parameters (classification of impurities is based on criterion 2) (a)  $d_{dust}$  (b)  $d_{trash}$  (c)  $feret_{min\ dust}$  (d)  $feret_{min\ trash}$  (e)  $feret_{max\ dust}$  (f)  $feret_{max\ trash}$ .

final treatment process to minimize the impact of contaminants on the visual of fabric, greater attention should be given to larger particles, as they are more likely to affect fabric appearance and quality.

Examples of impurities for dust particles and trash particles detected on the surface of woven fabric made from weft yarn spun from 100% CO waste are shown in Figs. 13 and 14. The impurities are sorted according to the maximal Ferret's diameter  $feret_{max}$ .

### Conclusion

The study investigated and analyzed the contamination of the fabric surface due to cotton waste open-end rotor yarn woven into the weft. The objective of this study is to assess the impact of cotton fibre quality on the quality



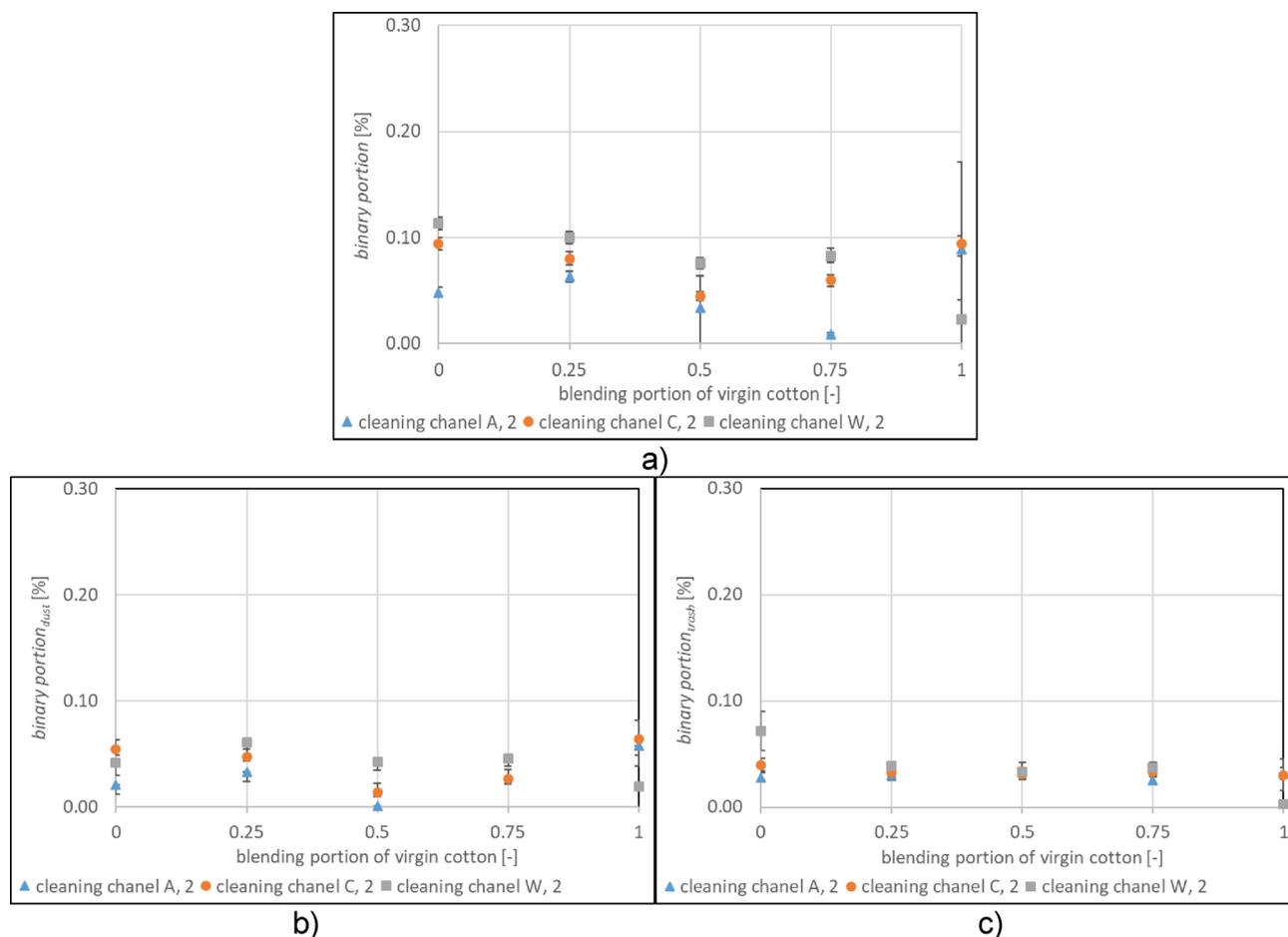
**Fig. 11.** Comparison of shape impurity parameters (a) shape factor  $q_{dust}$  (b) shape factor  $q_{trash}$  (c) the elongation  $e_{dust}$  (d) the elongation  $e_{trash}$ .

of yarns and fabrics, surface quality produced from them, with a particular focus on the degree of contamination. The research examines existing methods for evaluating contamination levels in raw cotton, yarns, and fabrics, aiming to identify and propose suitable qualitative and quantitative parameters for assessing impurities, particularly seed coat fragments and other plant residues. Furthermore, the study evaluates the significance of the blend ratio of reused cotton fibers and the cleaning processes applied during spinning, analyzing their effects on yarn quality and the resulting contamination of fabrics in a gray state. Additionally, it indirectly evaluates the potential hazard risk for environmental pollution by shedding or fibers, fiber fragments, plant impurities, and dust particles.

This study is a follow-up research examining the impact of cotton waste proportion and cleaning channels (A, C, W) used during the spinning of open-end rotor yarns on the quality of woven fabrics made from them in the weft direction. The study proves that cotton waste can be effectively incorporated into yarn production without significantly compromising fabric properties, supporting the sustainable use of recycled fibers. Moreover, more frequent cleaning of the weaving machinery is required to ensure a stable weaving process, minimize yarn breakages, and reduce contamination of the working environment.

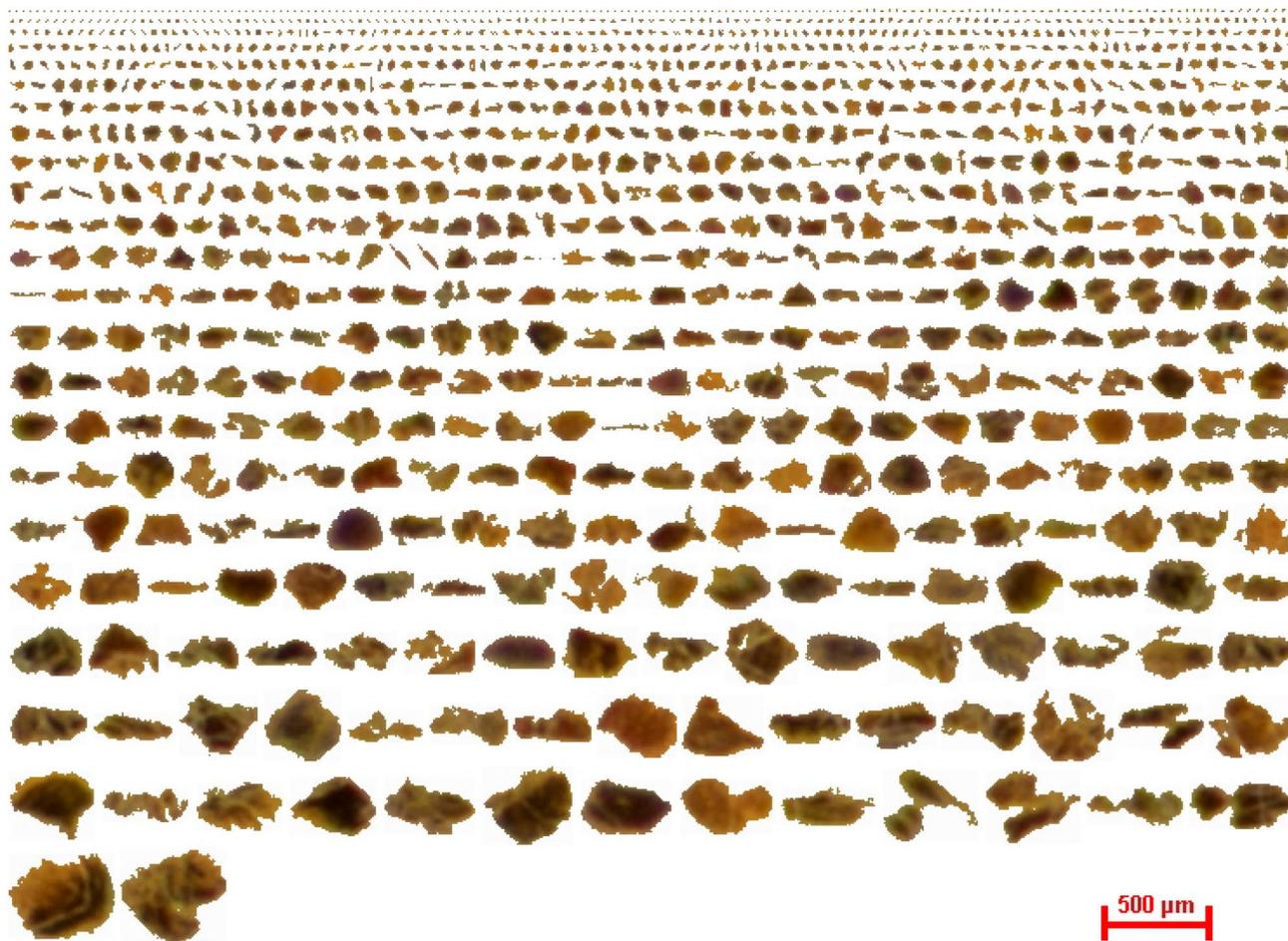
The findings confirm that yarn contamination does not fully translate into fabric contamination, as impurities are released throughout production, particularly due to friction and dynamic forces during weaving. The innovative cleaning channel W increases fiber yield but also raises contamination levels, leading to a higher number of detected impurities on the fabric surface. The classification method for dust and trash particles significantly affects the contamination evaluation, though contamination trends remain consistent. The classification of dust and trash particles by the maximal Ferret's diameter is preferred based on the obtained outputs from the realized experiment. Additionally, while the size of dust particles fixed in fabric structure decreases as the cotton waste proportion decreases, trash particle size is unaffected by the cleaning channel or waste ratio in the weft yarn. It also means that it can be expected that the particles decompose due to mechanical forces, and smaller particles are shed from the structure. The respirable dust is the most critical aspect for the risk of pulmonary infection of workers and has to be eliminated from the working area.

In the binary portion, the contaminant amount decreases as cotton waste content in weft yarns is reduced, with the lowest found in cleaning channel A, followed by C and W. Surprisingly, dust and trash particles contribute to the binary portion equally. This leads to the recommendation connected with optimizing fabric



**Fig. 12.** Comparison of the binary portion (classification of impurities is based on criterion 2) (a) binary portion (b) binary portion<sub>dust</sub> (c) binary portion<sub>trash</sub>.

quality: the final treatment should focus mainly on eliminating the visual impact of larger contaminants. The reason is that smaller particles can be mostly removed during pretreatment because they are not firmly fixed in a woven structure. At the industrial scale, the notable benefits of the presented results are their potential to indicate the level of fabric contamination, which is crucial for planning subsequent textile finishing processes, such as pretreatment, bleaching, and dyeing, particularly in terms of adjusting process parameters to effectively decolorization of residual seed coat fragments adhered to the fabric surface.



**Fig. 13.** Examples of detected dust particles on woven fabric made of weft yarn spun from 100% CO waste.



**Fig. 14.** Examples of detected trash particles on woven fabric made of weft yarn spun from 100% CO waste.

### Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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### References

1. Damayanti, D., Wulandari, L. A., Bagaskoro, A., Rianjanu, A. & Wu, H. S. Possibility Routes for Textile Recycling Technology, *Polymers*, vol. 13, no. 21, Art. no. 21, Jan. (2021). <https://doi.org/10.3390/polym13213834>
2. Duhoux, T. & the European Union. *Study on the technical, regulatory, economic and environmental effectiveness of textile fibres recycling: final report*. Publications Office of, Accessed: Mar. 04, 2025. [Online]. (2021). Available: <https://doi.org/10.2873/828412>
3. Esteve-Turrillas, F. A. & de la Guardia, M. Environmental impact of recover cotton in textile industry. *Resour. Conserv. Recycl.* **116**, 107–115. <https://doi.org/10.1016/j.resconrec.2016.09.034> (Jan. 2017).
4. Sandin, G. & Peters, G. M. Environmental impact of textile reuse and recycling – A review. *J. Clean. Prod.* **184**, 353–365. <https://doi.org/10.1016/j.jclepro.2018.02.266> (May 2018).
5. Telli, A. & Babaarslan, O. Commercialized denim fabric production with post-industrial and post-consumer wastes. *TEKSTİL VE KONEKSİYON* **26**(2), 213–220 (2016).

6. Yükkekkaya, M. E., Celep, G., Doğan, G., Tercan, M. & Urhan, B. A comparative study of physical properties of yarns and fabrics produced from Virgin and recycled fibers. *J. Eng. Fibers Fabr.* **11** (2). <https://doi.org/10.1177/155892501601100209> (2016).
7. Gun, A. D., Akturk, H. N., Macit, A. S. & Alan, G. Dimensional and physical properties of socks made from reclaimed fibre, *J. Text. Inst.*, vol. 105, no. 10, Art. no. 10, Oct. (2014). <https://doi.org/10.1080/00405000.2013.876152>
8. Ute, T. B., Celik, P. & Uzumcu, M. B. Utilization of Cotton Spinning Mill Wastes in Yarn Production, in *Textile Industry and Environment*, IntchOpen, Accessed: Mar. 05, 2020. [Online]. (2019). Available: <https://www.intechopen.com/books/textile-industry-and-environment/utilization-of-cotton-spinning-mill-wastes-in-yarn-production>
9. Halimi, M. T., Hassen, M. B., Azzouz, B. & Sakli, F. Effect of cotton waste and spinning parameters on rotor yarn quality, *J. Text. Inst.*, vol. 98, no. 5, Art. no. 5, Sep. (2007). <https://doi.org/10.1080/00405000701547649>
10. Hasani, H. & Tabatabaei, S. A. Optimizing Spinning Variables to Reduce the Hairiness of Rotor Yarns Produced from Waste Fibres Collected from the Ginning Process, *FIBRES & TEXTILES in Eastern Europe*, vol. 3(86), no. 19, Art. no. 19, 2011, Accessed: Mar. 02, 2020. [Online]. Available: <http://fibtex.lodz.pl/article517.html>
11. Kaplan, S. & Göktepe, Ö. Investigation into Navel Selection for Rotor Spinning Machine Using Cotton Waste, *FIBRES & TEXTILES in Eastern Europe*, vol. 14, no. 3(57), Art. no. 3(57), 2006, [Online]. Available: [http://www.fibtex.lodz.pl/file-Fibtex\\_\(14ia2894u043dtp1\).pdf](http://www.fibtex.lodz.pl/file-Fibtex_(14ia2894u043dtp1).pdf)
12. Christiani, D. C. et al. Mar., Longitudinal changes in pulmonary function and respiratory symptoms in cotton textile workers. A 15-yr follow-up study, *Am. J. Respir. Crit. Care Med.*, vol. 163, no. 4, pp. 847–853, (2001). <https://doi.org/10.1164/ajrccm.163.4.2006063>
13. Tageldin, M. A., Gomaa, A. A. & Hegazy, E. A. M. Respiratory symptoms and pulmonary function among cotton textile workers at Misr Company for Spinning and Weaving EL-Mahalla, Egypt, *Egypt. J. Chest Dis. Tuberc.*, vol. 66, no. 2, pp. 369–376, Apr. (2017). <https://doi.org/10.1016/j.ejcdt.2017.03.004>
14. Nagoda, M., Okpapi, J. U. & Babashani, M. Assessment of respiratory symptoms and lung function among textile workers at Kano textile mills, kano, Nigeria. *Niger J. Clin. Pract.* **15** (4), 373–379. <https://doi.org/10.4103/1119-3077.104505> (2012).
15. Vu, T. et al. Prevalence of Allergic Rhinitis and Individual Prevention Practices Among Textile Workers in Vietnam, *Glob. J. Health Sci.*, vol. 10, no. 7, pp. 1–43, 2018, Accessed: Mar. 04, 2025. [Online]. (2018). Available: <https://ideas.repec.org/a/ibn/gjhsjl/v10y17p43.html>.
16. Ha, T. T. T. et al. The cotton Dust-Related allergic asthma: prevalence and associated factors among textile workers in Nam Dinh province, Vietnam. *Int. J. Environ. Res. Public Health.* **18** (18), 9813. <https://doi.org/10.3390/ijerph18189813> (Sep. 2021).
17. Krupincová, G. & Pechová, M. The quality comparison of open-end rotor-spun yarns produced from cotton waste in Gray state and after dyeing. *Text. Res. J.* **93**, 9–10. <https://doi.org/10.1177/00405175221141112> (May 2023).
18. Krupincová, G. The influence of various portion of cotton waste and way of cleaning on quality of open-end rotor yarns, in *STRUTEX Structure and Structural Mechanics of Textile Fabrics*, Liberec, p. 9. <https://doi.org/10.15240/tul/002/9788074947179>
19. Krupincová, G. Assessment of the effects of the use of preconsumer cotton waste on the quality of rotor yarns, *Heliyon*, vol. 10, no. 15, p. e34482, Aug. (2024). <https://doi.org/10.1016/j.heliyon.2024.e34482>
20. USTER AFIS PRO – What does the data mean? Uster Technologie AG. [Online]. Available: [www.uster.com/Feb.](http://www.uster.com/Feb.) (2004).
21. Uster TESTER 5 The yarn inspection system. Uster Technologies AG, Switzerland, (2013).
22. Li, M., Fang, G., Xu, C. & Hinks, D. Image-Based analysis of seed coat fragments in cotton fabrics. *AATCC J. Res.* **3** (1), 14–20. <https://doi.org/10.14504/ajr.3.1.3> (Jan. 2016).
23. Bel, P. D., Xu, B. & Boykin, D. Automatic detection of seed coat fragments in cotton fabrics, *Text. Res. J.*, vol. 82, no. 16, pp. 1711–1719, Oct. (2012). <https://doi.org/10.1177/0040517511433153>
24. Bel, P. D. & Xu, B. Measurements of seed coat fragments in cotton fibers and fabrics, *Text. Res. J.*, vol. 81, no. 19, pp. 1983–1994, Nov. (2011). <https://doi.org/10.1177/0040517511407370>
25. Meloun, M. & Militký, J. *Chemometrics For Analytical Chemistry: Volume I PC-Aided Statistical Data Analysis*, 1992nd ed., 1st edition vols. Ellis Horwood Ltd.
26. Uster Statistics. - benchmarks from fiber to yarn - Uster Technologies AG. Accessed: Feb. 26, 2025. [Online]. Available: <https://www.uster.com/value-added-services/uster-statistics/>

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## Author contributions

Gabriela Krupincová came up with the idea of an experiment, analyzed the quality of yarn and fabric samples, processed the data, prepared the draft of the text, participated in its finalization, and is the corresponding author. Brigita Kolčavová Širková prepared the woven samples and realized their production, participated in data evaluation and drafted the manuscript preparation as well as its finalization. The authors declare that the article's publication is approved by all authors.

## Declarations

## Competing interests

The authors declare no competing interests.

## Additional information

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