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Sterilization of PAN/Gelatine Nanofibrous Mats for Cell Growth

Sterilizacija PAN/želatinskih nanovlaknastih kopren za rast celic

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Abstract

Nanofibrous mats can be used as a substrate for eukaryotic cell growth in biotechnology, tissue engineering, etc. Several adherent cells (e.g. human fibroblasts) have been shown to grow well on fine fibres. For most applications, it is necessary to sterilize nanofibrous mats before adding the cells. Another possibility would be the addition of antibiotics and antimycotics to the cell culture medium to prevent microbial infection. However, antibiotics are disadvantageous since they might promote the growth of resistant bacteria in possible future medical applications of nanofibrous mats. Possible sterilization techniques include autoclaving, UV-sterilization, ozone treatment, heat sterilization and other techniques which usually necessitate more expensive equipment, such as gamma irradiation. Systematic examinations of the influence of different sterilization techniques on the cell growth on nanofibrous mats have not yet been reported in the literature. Here, we report on the first experimental investigations of the effect of sterilization with different methods on the properties of polyacrylonitrile (PAN)/gelatine nanofibrous mats, and the resulting growth and adhesion of Chinese hamster ovary cells. While all techniques under investigation yielded sterile nanofibrous mats, autoclaving and heat sterilization change the PAN/gelatine fibre morphology. Ozone, on the other hand, modifies the pH value of the culture medium and partly impedes cell adhesion. UV sterilization also suggests a chemical modification of the nanofibrous mat. Unexpectedly, heat sterilization resulted in the highest amount of adherent Chinese hamster ovary cells grown on PAN/gelatine nanofibrous mats in spite of gelatine melting.

Keywords: polyacrylonitrile/gelatine nanofibrous mats, sterilization, autoclaving, ozone, UV sterilization, heat sterilization, cell growth, adherent cells, CHO cells, tissue engineering

Izvleček

Nanovlaknaste koprene se lahko uporabijo kot substrat za rast celic v biotehnologiji, tkivnem inženirstvu itd. Pokazalo se je, da številne celice, npr. človeški fibroblasti, pritrjene na finih vlaknih, dobro rastejo. Za večino aplikacij je treba nanovlaknaste koprene pred nanosom celic sterilizirati. Druga možnost preprečevanja mikrobnih okužb bi bila dodajanje antibiotikov in antimikotikov v gojišče celične kulture. Vendar pa so antibiotiki manj primerni, saj lahko spodbujajo rast odpornih bakterij v morebitnih prihodnjih medicinskih aplikacijah nanovlaknastih kopren. Mogoče so različne tehnike sterilizacije, vključno z avtoklaviranjem, UV-sterilizacijo, obdelavo z ozonom, toplotno sterilizacijo in druge, ki po navadi zahtevajo dražjo opremo, kot je obsevanje z žarki gama. Pregleda o vplivu različnih tehnik sterilizacije na rast celic na nanovlaknastih koprenah v literaturi še ni. V nadaljevanju predstavljamo prve eksperimentalne raziskave učinka sterilizacije z različnimi metodami na lastnosti poliakrilonitrilnih (PAN)/želatinastih nanovlaknastih kopren in posledično na rast in adhezijo celic. Medtem ko so tehnike, ki so bile raziskane, omogočile

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izdelavo sterilnih nanovlaknastih kopren, pa sta avtoklaviranje in toplotna sterilizacija spremenila morfologijo PAN/želatinastih vlaken. Po drugi strani pa je ozon spremenil vrednost pH-gojišča in delno oviral celično adhezijo. UV-sterilizacija je vodila tudi v kemično modifikacijo nanovlaknaste koprene. Nepričakovano je bilo, da je toplotna sterilizacija vodila v nastanek največje količine celic jajčnikov kitajskega hrčka (celice CHO), ki kljub taljenju želatine rastejo na PAN/želatinastih nanovlaknih.
Ključne besede: PAN/želatinska nanovlakna, sterilizacija, avtoklaviranje, ozon, UV-sterilizacija, toplotna sterilizacija, rast celic, adherentne celice, celice CHO, tkivni inženiring

1 Introduction

Nanofibrous mats with the fibre diameters in the range of some ten to several hundred nanometres can be prepared with electrospinning from diverse polymer solutions or melts. While the easiest technology uses a syringe to extrude the polymer solution through a fine needle into a high electric field [1, 2], needleless technologies allow for higher production output and can often be upscaled from lab to industrial scale [3–5].
Electrospinning from a solution necessitates finding an adequate solvent to dissolve the desired polymer or polymer blend, besides several other prerequisites, such as large enough molecular weight of the polymer to form fibres at all. Several solvents which are often used in electrospinning, however, are toxic or corrosive. While a large number of biopolymers can be electrospun from water [6, 7], only few water-resistant polymers can be spun from low-toxic solvents such as dimethyl sulfoxide (DMSO) [8]. This is one of the reasons why polyacrylonitrile (PAN) is of large interest in electrospinning, apart from its usability as a precursor for carbon nanofibres [9–11].
Preliminary tests in our group showed that animal cells do not grow well on pure PAN nanofibrous mats although serum was added to the culture medium. It is well-known that certain proteins present in the serum promote cell adhesion (e.g. fibronectin [12]). Another possibility to enable cell adhesion is coating the cell culture flasks with collagen, which is an established method to enable cell adhesion [13]. Thus, the effect of adding gelatine to the PAN solution was tested. Commercially available gelatine is derived mostly from porcine skin. It is water-soluble, and consists mainly of a mixture of different denatured and partly hydrolysed collagens. PAN/gelatine nanofibres display slightly increased fibre diameters compared to pure PAN nanofibres [14]. Since the exact distribution of both components in fibres has not been investigated yet, the influence of the fluid culture medium on fibre integrity has to be examined.
Generally, nanofibrous mats prepared from biopolymers, such as gelatine or alginate, are known to support cell growth for wound healing, tissue engineering or biotechnological purposes [15–19]. Especially for elongated cells, such as neurites or fibroblasts, nanofibres have been shown to support cell growth [20–24].
Unexpectedly, possibilities to sterilize nanofibrous mats before the addition of cells and their potential influences on cell growth are only scarcely mentioned in the scientific literature. Castagna *et al* performed autoclaving and UV irradiation to sterilize polyaniline nanofibrous mats [25]. Arnal-Pastor *et al* used immersion in 70% ethanol for 3 hours, which necessitated careful rinsing with sterile phosphate-buffered saline to remove ethanol residues, making this method very time-consuming [26]. Ethanol was also suggested by Fan *et al* to sterilize regenerated silk fibroin nanofibres [27]. However, absolute ethanol (99.46%) is usually non-sterile since it is known to preserve microbial spores [13]. Therefore, sterilization with ethanol is not a reliable procedure.
In this paper, we report on a comparison of four different sterilization techniques applied for PAN/gelatine nanofibrous mats, and their influence on the growth of adherent CHO cells in the absence of antibiotics and antimycotics. The CHO cells are often used in the production of therapeutic proteins and in diverse biotechnological examinations [28–31]. Hence, they are ideal model cells for preliminary sterility tests.

2 Materials and methods

2.1 Electrospinning

Nanofibrous mats were produced with the wire-based electrospinning machine "Nanospider Lab" (Elmarco, Liberec, Czech Republic). The spinning parameters were: voltage 70 kV, nozzle diameter 1.5 mm, carriage speed 100 mm/s, static substrate, ground-substrate distance 240 mm, electrode-substrate distance 50 mm, relative humidity 33%, spinning duration 50 min.

The PAN solutions were prepared with a PAN (purchased from Woolworth, Unna, Germany) concentration of 16% in DMSO (min. 99.9%, purchased from S3 Chemicals, Bad Oeynhausen, Germany) by two-hour stirring at room temperature. Gelatine (purchased from Abtei, Marienmünster, Germany) was added in the concentrations of 5% and 10%; higher concentrations were not spinnable.

2.2 Sterilization

Sterilization was performed with the following methods:

A closed box with an ozone generator (CHM GmbH, Amberg, Germany), working according to ISO 105-G03, was used for 15 min, 30 min, 45 min and 60 min. Afterwards, the petri dishes were closed inside the box to avoid contaminations after the sterilization process.

The heat sterilization was performed with an oven UN75 (Memmert, Schwabach, Germany) at the temperatures of 60 °C, 100 °C, 140 °C and 180 °C for 30 min each.

For the UV sterilization, a UV lamp UV-spot 25W/E27 (Eurolite, Waldbüttelbrunn, Germany) was used. Since this lamp was not specified for sterilization, relatively long irradiation times of 1 h, 1.5 h, 2 h, 2.5 h and 4 h were tested. The heat development during the sterilization was monitored with a thermal camera (FLIR E8, FLIR Systems, Wilsonville, OR, USA).

The autoclaving was performed for 20 min at 121 °C with a VX-75 autoclave obtained from Systec (Linden, Germany).

Before the sterilization tests, the nanofibrous mat samples were washed three times with highly purified water. After the sterilization, the samples were placed in the wells of a 24-well cell culture plate (Cellstar®, Greiner, Kremsmünster, Austria) inside a biological safety cabinet Safe 2020 (Thermo Electron LED GmbH, Langenselbold, Germany). Prior to that, 5 ml of mediums was pipetted into the well, using five specimens per experiment. One well was used as a sterility test. The incubation was performed for 4 days (96 h) in a HERAcell 240i incubator (ThermoFisher Scientific, Waltham, MA, USA) at 37 °C and 7.5% CO_2.

2.3 Cell cultivation

For the cell cultivation, Dulbecco's Modified Eagle's medium (DMEM) / Ham's Nutrient Mixture F12 (1 : 1 DMEM/F12) (purchased from SAFC Biosciences, Irvine, UK) was used as a base. The medium was prepared according to the instructions for use. It was supplemented with glucose (Roth, Karlsruhe, Germany) and L-glutamine (Applichem, Darmstadt, Germany) to the final concentration of 4 g/l and 4 mM, respectively. It also contained phenyl red. The pH value was set to 7.4 before the medium was sterile filtered (Sartolab P, 0.45 µm / 0.22 µm, Sartorius, Göttingen, Germany). Finally, 10% sterile donor horse serum (biowest, Nuaillé, France) was added.

The CHO DP-12 cells used in this study were obtained from LGC Standards GmbH, Wesel, Germany (ATCC no. CRL-12445). These Chinese hamster ovary cells grow *in vitro* to form a monolayer if using a serum containing medium.

For the cell cultivation, nanofibrous mat samples of 2 cm × 2 cm were glued with Elastosil E41 RTV-1 silicone rubber (Wacker, Burghausen, Germany) on cover slips (21 mm × 26 mm) (Carl Roth, Karlsruhe, Germany) to keep them inside the medium. After the sterilization, the mats were placed in 6-well plates (Labsolute, Th. Geyer, Renningen, Germany) inside a safety cabinet (HERA Safe 2020, ThermoFisher Scientific, Waltham, MA, USA). 200,000 cells were seeded into each well. In one well, only cells without a nanofibrous mat were cultivated as a control. The cultivation was again performed for 4 days in an incubator at 37 °C and 7.5% CO_2.

Afterwards, the medium was pipetted out of the wells. The cells were dyed with 1 ml methylene blue (euromex, Arnheim, Netherlands; 1 : 16 dilution in PBS). The pretests showed that neither PAN nor gelatine were dyed by it, confirming that all blue objects on nanofibrous mats must belong to cells (not shown).

After PBS was again pipetted out of the wells, 1.5 ml glyoxal solution was added to fix the cells [32]. For this, a 3 vol% glyoxal solution, containing 34.02 ml highly purified water, 9.468 ml ethanol (abs., VWR BDH Prolabo, Langenfeld, Germany), 3.756 ml 40% glyoxal (Roth, Karlsruhe, Germany) and 0.36 ml acetic acid p.a. (VWR BDH Prolabo, Langenfeld, Germany), with the pH value between 4 and 5 was used. The well plate was cooled on ice for 30 min and incubated for another 30 min at room temperature before the glyoxal solution was pipetted out of the wells, and the nanofibrous mats were taken out and dried in the air.

2.4 Investigations

An optical examination during cultivation was achieved with an Axiovert 40 CFL microscope (Zeiss, Oberkochen, Germany). After the fixation, confocal laser scanning microscopes (CLSM) VK-9000 and VK-100 (Keyence, Osaka, Japan) were used with the nominal resolution of 2000×.

The number of attached cells on nanofibrous mats was counted with a Neubauer chamber (Hecht Assistent, Sondheim, Germany). The nanofibrous mats were carefully washed with PBS and then treated with a sterile trypsin/EDTA (ethylenediamine tetraacetic acid) solution (biowest, Nuallié, France), digesting the cell-matrix interaction, which results in cell detachment. After 5 min incubation at 37 °C, the trypsinization was stopped by diluting the fluid with a culture medium. A 50 µl cell suspension was mixed with 50 µl trypan blue (a vital stain used to colour the dead cells blue) and the cells were counted with a Neubauer chamber.

3 Results and discussion

The sterilization test (Figure 1) revealed a colour change of the medium in the wells in which the ozone-sterilized specimens were placed. The medium contained phenyl red, a pH indicator. At neutral pH, phenyl red displays a pink colour. When the pH is lowered, the colour of the indicator changes to yellow. In the cell culture technology, this is useful since the change in colour indicates that the nutrients are used up by the cells. Here, no cells were added to nanofibrous mats. Nevertheless, the colour change was observed. This can be attributed to the highly reactive ozone molecules that produced radicals which were able to react with the fibres to change the pH value of the surrounding medium.

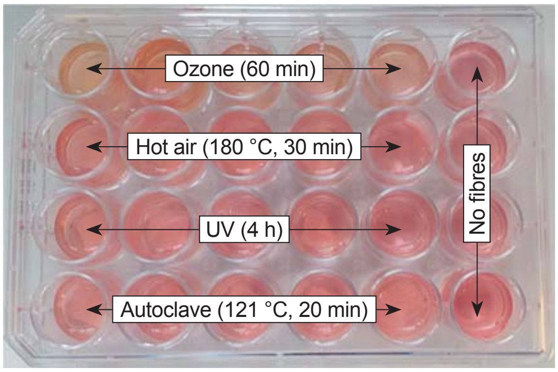


Figure 1: Sterilization test, photograph taken on day 0; four wells were incubated without fibre mats as control ("no fibres")

This effect was only visible directly after the addition of medium; however, on the following day, all wells displayed the same colour as shown here for the not ozone-treated nanofibrous mats, without changing the medium. The medium contained a carbonate buffer system. Since the incubation took place in a CO_2 atmosphere (7.5%), all pH values changed to the same level. It should be mentioned that in the following test series in which all nanofibrous mats were washed with high-purity water before the sterilization, this finding was only slightly visible, indicating that either DMSO or pure gelatine, which could be washed off, was responsible for the effect. Shorter ozone treatment durations also reduced this effect significantly.

Next, the influence of the sterilization processes and the culture medium on the nanofibrous mat morphologies was tested by CLSM imaging. Figure 2 shows a PAN/gelatine nanofibrous mat before the sterilization, with typical fibre diameters in the range 400–800 nm for both gelatine concentrations, with several thicker fibres on the surface, which were dissolved at higher temperatures, indicating that they mostly consisted of gelatine, while former stabilization test series indicated that most fibres contained a blend of PAN and gelatine, which was water-stable [10]. Figure 3 depicts the results after the sterilization with different methods and immersion in a culture medium.

Figure 2: CLSM image of PAN/gelatine nanofibrous mat with 10% gelatine after electrospinning; scale bar indicates 20 µm

Firstly, it was clearly visible that the hot air treatment and autoclaving changed the morphology of

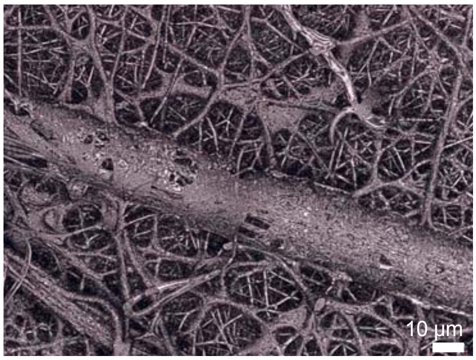
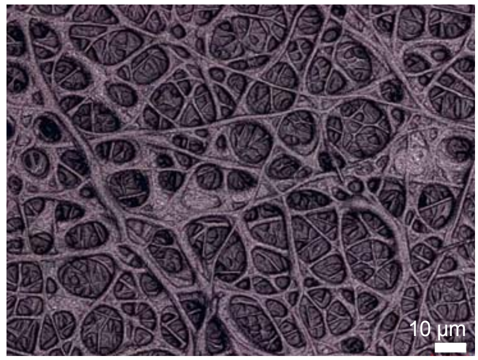
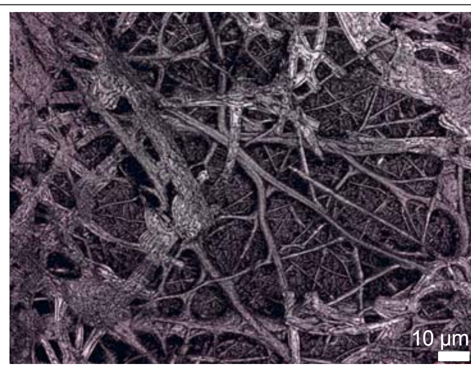
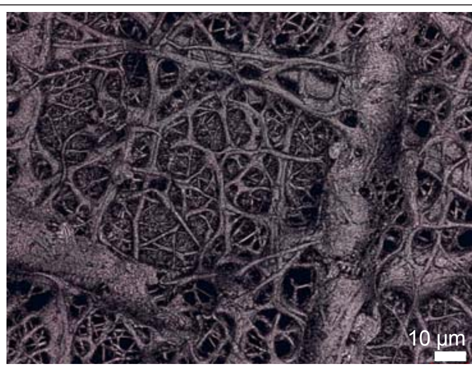
Sterili-zation technique	After sterilization	After culture medium
Ozone (60 min)		
Hot air (180 °C, 30 min)		
UV (4 h)		
Autoclave (121 °C, 20 min)		

Figure 3: CLSM images of nanofibrous mats taken after sterilization and after following immersion in culture medium; scale bars indicate 10 µm

fibres. In both cases, gelatine was molten and afterwards solidified again, as described above. A higher temperature used for autoclaving seemed to slightly reduce the viscosity of the molten gelatine and correspondingly increased its spreading over the near environment before the re-solidification.

This could be expected since gelatine was shown to start melting at the temperatures around 32–40 °C [33], the temperature range which was exceeded in both processes. It should be mentioned that during the cell cultivation at 37 °C, gelatine could also be assumed to be molten. In addition, similar changes were visible in parts with UV-sterilized nanofibrous mats, which could be attributed to the hot UV lamp positioned very close to the samples, resulting in the temperature on the sample surface of about 32–36 °C, as measured with a thermal camera.

After the ozone treatment, the relatively thick, long gelatine fibres could clearly be distinguished from the PAN or PAN/gelatine fibres. Previous research revealed that in most fibres, PAN and gelatine were mixed [14]; however, in all cases, pure gelatine fibres were also found in PAN/gelatine nanofibrous mats as visible in the confocal laser scanning microscope images after the stabilization of fibre blends. In these former test series, PAN/gelatine nanofibre mats were stabilized at different temperatures and heating rates, resulting in a clear colour differentiation between the afterwards brown PAN and the silvery gelatine. This enabled distinguishing between both materials optically, instead of using chemical microscopic methods. The morphology of these nanofibrous mats was not different from the one of the original mat.

After the incubation of the ozone treated nanofibrous mat in a culture medium, the thickest fibres were still visible, underlining that they contained PAN as well, since pure gelatine fibres would be expected to dissolve in an aqueous culture medium.

After the general proof that these sterilization methods were applicable to PAN/gelatine nanofibrous mats, shorter treatment times (in the case of ozone and UV sterilization) or lower temperatures (in the case of hot air sterilization) were investigated. In the following cases, contaminations occurred, namely at 15 min of ozone treatment (1 of 5 samples was contaminated), 60 °C heat treatment (6 of 10 samples), 2.5 h of UV treatment (2 of 10 samples), 2.0 h of UV treatment (1 of 10 samples), 1.5 h of UV treatment (1 of 10 samples) and 1 h of UV treatment (2 of 10 samples).

These numbers of contaminated samples exhibited that only for the heat treatment at 60 °C, the sterilization did not work for most samples. In other cases, nanofibrous mats were sterilized at high percentage. While this clearly shows that autoclaving – as the standard method – is still preferable in terms of sterility, the ozone and UV treatments resulted in significantly better maintaining of the nanofibre structure and they can thus be assumed to be more eligible with respect to cell growth. While the sterility in the range of 90% is inacceptable for medical purposes, it may be tolerable for basic research on cell cultures. For the special application of nanofibrous mats for cell growth and cell adhesion, the statistical sterilization success and the dimensional stability of nanofibrous mats have to be balanced. Future investigations will examine the statistical sterilization success of these milder treatments in detail.

For the final cell culturing experiments, the original sterilization temperatures and durations, respectively (Figure 3), were adopted. Figure 4 depicts exemplarily one experiment in which CHO DP-12

a) b)

Figure 4: 6-well plate with ozone-sterilized nanofibrous mats (10% gelatine) in culture medium (only medium in lower right well as reference) with CHO DP-12 cells, (a) start of cultivation, (b) end of cultivation at day 5

cells were cultivated on ozone-sterilized nanofibrous mats containing 10% gelatine. Similar results were gained with 5% gelatine content; a quantitative comparison is given later on.

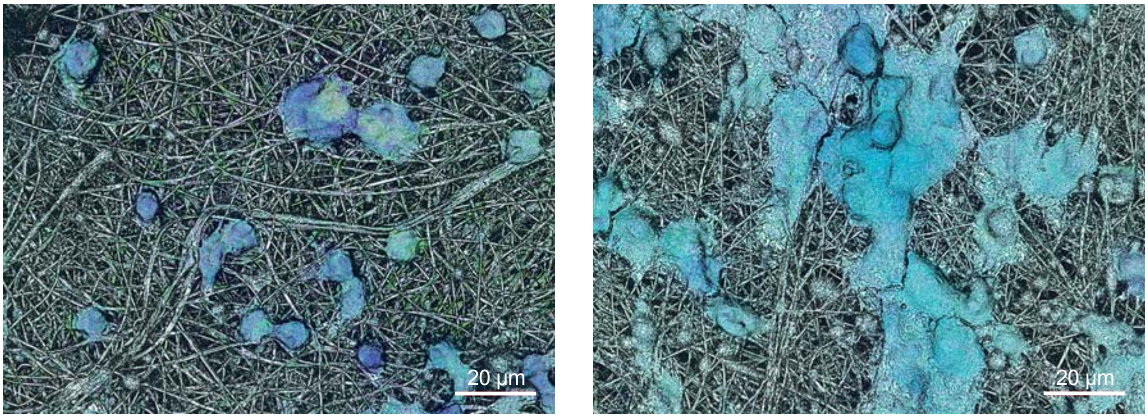


Figure 5: CLSM images of CHO DP-12 cells on different areas of ozone-sterilized PAN/gelatine nanofibrous mats; scale bars indicate 20 µm

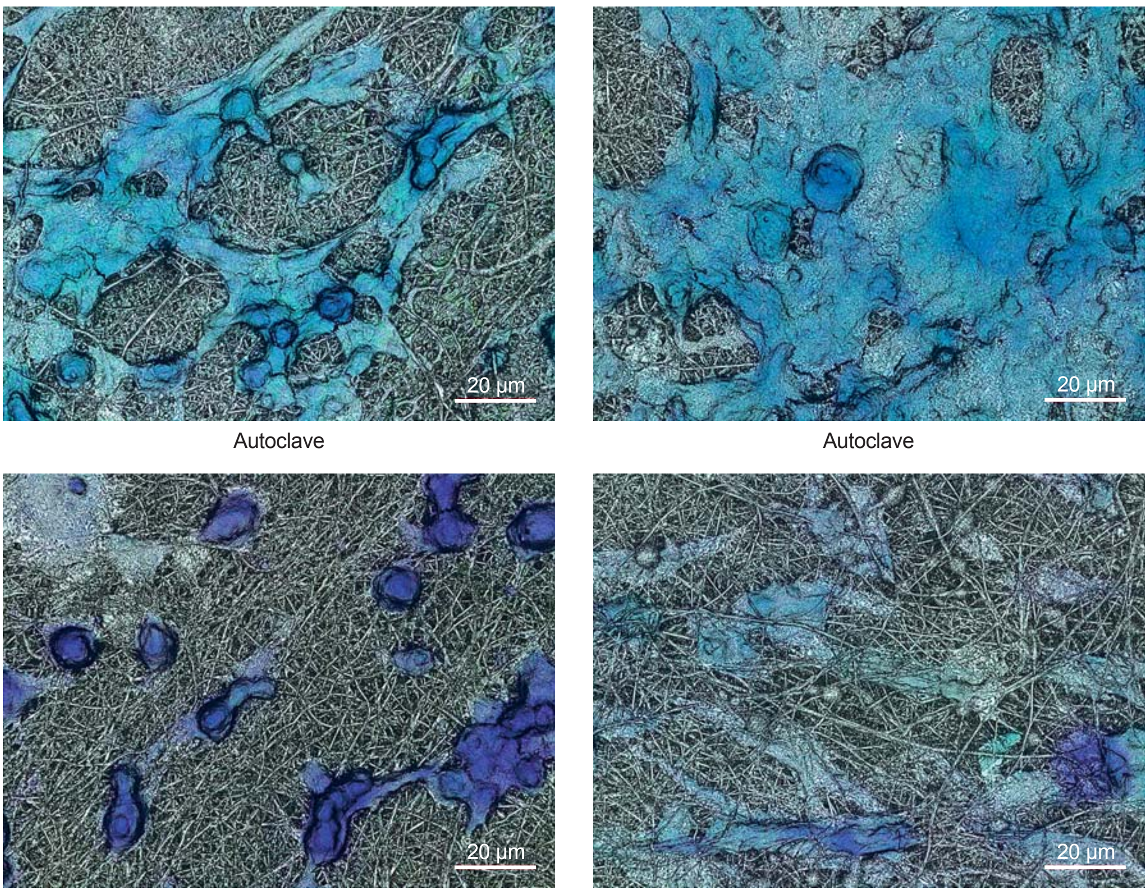


Figure 6: CLSM images of CHO DP-12 cells on different areas of PAN/gelatine nanofibrous mats sterilized with different methods; scale bars indicate 20 µm

Firstly, different colours at the end of cultivation indicate that the cell growth occurred unequally in different wells. The colour change is based on the change in the pH value, as discussed before in the case of ozone-treated samples. Here, however, the nutrient consumption of cells resulted in this pH change, indicating that the wells where the colour of the medium changed to yellow will show the highest cell concentration. Comparing the reference well (lower right) with the others, the cell growth seems to be reduced on ozone-sterilized nanofibrous mats.

Figure 5 depicts the CLSM images of CHO DP-12 cells on ozone-sterilized nanofibrous mats with 10% gelatine. The small, round cells seem to be only punctually adhered, while the larger bluish zones show flattened adherent cells where the cytoplasm spread over a larger area. Non-adherent and punctually adhered CHO DP-12 cells have dimensions of approximately 12–17 μm, while the adhered cells in the control wells were measured to have the lengths of approx. 65 μm due to their fibroblast-like morphology (not shown).

In the same way, the other three sterilization methods were examined. Figure 6 shows the CHO DP-12 cells on some of these sterilized nanofibrous mats. While the hot air treatment mostly showed small and thus poorly adhered cells, good cell attachment was achieved by autoclaving.

Interestingly, in the case of UV sterilization, partly only a very fine blue layer was visible which may be the cell residues or cell products which are embedded in the nanofibrous mat and fixed by the glyoxal solution.

These CLSM images suggest that autoclaving is the best sterilization technology for the growth of CHO DP-12 cells on PAN/gelatine nanofibrous mats.

To quantitatively examine this question, adherent cells on PAN/gelatine nanofibrous mats with 5% and 10% gelatine were detached by trypsin and subsequently counted using a Neubauer chamber. The results are depicted in Figure 7. It should be mentioned that the cell counting with a Neubauer chamber is usually assumed to have the statistical uncertainty of 20%; this value was used for the error bars.

Firstly, on the nanofibrous mats with 10% gelatine, slightly higher cell concentrations were found. However, as the error bars indicate, this tendency is not significant.

For both gelatine concentrations, ozone gave the worst results, which might be related to the observed pH change in the culture medium, suggesting chemical changes in the nanofibrous mat, which apparently suppressed the cell growth. This finding fits well with the observation in Figure 5, showing only few cells on ozone-treated nanofibrous mats. While Figure 6 suggested that autoclaving would be the ideal sterilization method, the cell counting revealed that the hot air sterilization worked even better. Comparing the respective images in Figure 6, one possible explanation is that during the cell counting with a Neubauer chamber, larger and smaller cells are counted in the same way, while the adherent cells cover larger areas on nanofibrous mats and thus give the impression that more cells are grown on autoclaved nanofibrous mats. Another explanation could be that the cells were not fully detached by trypsinization on autoclaved nanofibrous mats due to tighter binding.

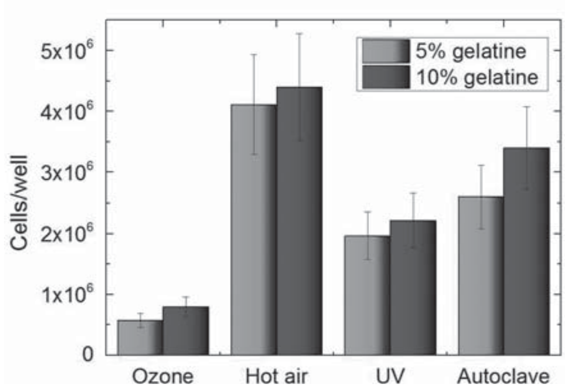


Figure 7: Cell numbers after 4 days of cultivation on differently sterilized nanofibrous mats, counted with Neubauer chamber after trypsinization (N = 2)

Combining all findings presented in this study, it can be concluded that the heat treatment methods, i.e. hot air and autoclaving, are preferable to chemical methods, i.e. ozone treatment, or physical methods, i.e. UV irradiation. One possible explanation for this finding is the partial melting of gelatine during the heat treatment that creates larger areas in which more gelatine is exposed on the surface of nanofibres, making it accessible to cells for attachment; an effect which would even be visible to a certain extent in UV-treated nanofibrous mats due to the heat development of the UV source, as described above. This idea corresponds to the tendency towards slightly larger cell concentrations on nanofibrous mats with higher gelatine content and previous findings of a student project (unpublished) that the CHO DP-12 cells do not grow at all on pure PAN nanofibrous mats.

4 Conclusions and outlook

PAN/gelatine nanofibrous mats were prepared by needleless electrospinning and sterilized using ozone, hot air, UV irradiation and autoclaving. While the hot air treatment, even at only 60 °C, and autoclaving melted gelatine and thus changed the morphology of nanofibrous mats, the ozone sterilization suggested a change in the nanofibrous mat chemistry. Unexpectedly, the degree of gelatine melting at high temperatures seemed to correlate with the cell attachment, resulting in the hot air treatment showing the best cell growth, while the ozone sterilization (the only method without a thermal component) resulted in the poorest cell growth. For all sterilization methods, the cell growth and attachment on PAN/gelatine blends is possible, opposite to pure PAN nanofibrous mats, as shown by previous experiments.

These findings suggest further chemical examinations, especially of the ozone treated samples, as well as an optimization of the electrospinning process to include more gelatine in nanofibrous mats. Finally, different temperature treatments in a broader temperature range will be investigated to optimize the cell growth conditions.

References

1. GREINER, Andreas, WENDORFF, Joachim H. Electrospinning: a fascinating method for the preparation of ultrathin fibers. *Angewandte Chemie International Edition*, 2007, **46**(30), 5670–5703, doi: 10.1002/anie.200604646.
2. LI D., XIA, Y. Electrospinning of nanofibers: reinventing the wheel? *Advanced Materials*, 2004, **16**(14), 1151–1170, doi: 10.1002/adma.200400719.
3. YALCINKAYA, Fatma, YALCINKAYA, Baturalp, JIRSAK, Oldrich. Influence of salts on electrospinning of aqueous and nonaqueous polymer solutions. *Journal of Nanomaterials*, 2015, **2015**(5), 134251, doi: 10.1155/2015/134251.
4. MILASIUS, Rimvydas, RAGAISIENE, Audrone, RUKUIZIENE, Zaneta, MIKUCIONIENE, Daiva. Possibilities of manufacturing an electrospun web with baltic amber. *FIBRES & TEXTILES in Eastern Europe*, 2015, **5**(113), 42–47.
5. MOLNAR, Kolos, NAGU, Zsombor K. Corona-electrospinning: Needleless method for high-throughput continuous nanofiber production. *European Polymer Journal*, 2016, **74**, 279–286, doi: 10.1016/j.eurpolymj.2015.11.028.
6. GROTHE, Timo, GROßERHODE, Christina, HAUSER, Thomas, KERN, Philip, STUTE, Kai, EHRMANN, Andrea. Needleless electrospinning of PEO nanofiber mats. *Advances in Engineering Research*, 2017, **102**, 54–58, doi: 10. 2991/icmmse-17.2017.9.
7. GRIMMELSMANN, Nils, HOMBURG, Sarah Vanessa, EHRMANN, Andrea. Electrospinning chitosan blends for nonwovens with morphologies between nanofiber mat and membrane. *IOP Conference Series: Materials Science and Engineering*, 2017, **213**(1), 012007, doi: 10.1088/1757-899X/213/1/012007.
8. WORTMANN, Martin, FREESE, Natalie, SABANTINA, Lilia, PETKAU, Richard, KINZEL, Franziska, GÖLZHÄUSER, Armin, MORITZER, Elmar, HÜSGEN, Bruno, EHRMANN, Andrea. New polymers for needleless electrospinning from low-toxic solvents. *Nanomaterials*, 2019, **9**(1), 52, doi: 10.3390/nano9010052.
9. MADDAH, Bozorgmehr, SOLTANINEZHAD, Mostafa, ADIB, Korosh, HASANZADEH, Mahdi. Activated carbon nanofiber produced from electrospun PAN nanofiber as a solid phase extraction sorbent for the preconcentration of organophosphorus pesticides. *Separation Science and Technology*, 2017, **52**(4), 700–711, doi: 10.1080/01496395.2016.1221432.
10. PANTHI, Gopal, PARK, Soo-Jin, CHAE, Su-Hyeong, KIM, Tae-Woo, CHUNG, Hea-Jong, HONG, Seong-Tshool, PARK, Mira, KIM, Hak-Yong. Immobilization of Ag_3PO_4 nanoparticles on electrospun PAN nanofibers via surface oximation: Bifunctional composite membrane with enhanced photocatalytic and antimicrobial activities. *Journal of Industrial and Engineering Chemistry*, 2017, **45**, 277–286, doi: 10.1016/j.jiec.2016.09.035.
11. GROTHE, Timo, WEHLAGE, Daria, BÖHM, Tobias, REMCHE, Alexander, EHRMANN, Andrea. Needleless electrospinning of PAN nanofibre mats. *Tekstilec*, 2017, **60**(4), 290–295, doi: 10.14502/Tekstilec2017.60.290-295.

12. RICHARDSON, Sarah A., RAWLINGS, Thomas M., MUTER, Joanne, WALKER, Marc, BROSENS, Jan J., CAMERON, Neil R., EISSA, Ahmed M. Covalent attachment of fibronectin onto emulsion-templated porous polymer scaffolds enhances human endometrial stromal cell adhesion, infiltration and function. *Macromolecular Bioscience*, 2019, **19**(2), e1800351, doi: 10.1002/mabi.201800351.
13. GSTRAUNTHALER, Gerhard, LINDL, Toni. Zell- und Gewebekultur. 7th edition. Berlin : Springer, 2013.
14. SABANTINA, Lilia, WEHLAGE, Daria, KLÖKKER, Michaela, MAMUN, Al, GROTHE, Timo, GARCÍA-MATEOS, Francisco José, RODRÍGUEZ-MIRASOL, José, CORDERO, Tomás, FINSTERBUSCH, Karin, EHRMANN, Andrea. Stabilization of electrospun PAN/gelatin nanofiber mats for carbonization. *Journal of Nanomaterials*, 2018, **2018**, 6131085, doi: 10.1155/2018/6131085.
15. PAMESHBABU, Arun Prabhu, DATTA, Sayanti, BANKOTI, Kamakshi, SUBRAMANI, Elavarasan, CHAUDHURY, Koel, LALZAWMLIANA, V., NANDI, Samit K., DHARA, Santanu. Polycaprolactone nanofibers functionalized with placental derived extracellular matrix for stimulating wound healing activity. *Journal of Materials Chemistry B*, 2018, **6**(42), 6767−6780, doi: 10.1039/C8TB01373J.
16. SHAKIBAIE, Mehdi, TABANDEH, Faterneh, SHARIATI, Parvin, NOROUZY, Amir. Synthesis of a thin-layer gelatin nanofiber mat for cultivating retinal cell. *Journal of Bioactive and Compatible Polymers*, 2018, **33**(4), 371−381, doi: 10.1177/0883911518776337.
17. ZHU, Caihong, ZHU, Junhui, WANG, Chengwei, CHEN, Ruihua, SUN, Lining, RU, Changhai. Wrinkle-free, sandwich, electrospun PLGA/SF nanofibrous scaffold for skin tissue engineering. *IEEE Transactions on Nanotechnology*, 2018, **17**(4), 675−679, doi: 10.1109/TNANO.2018.2801569.
18. ALIPPILAKKOTTE, Shebi, SREEJITH, Lisa. Benign route for the modification and characterization of poly(lactic acid) (PLA) scaffolds for medicinal applications. *Journal of Applied Polymer Science*, 2018, **135**(13), 46056, doi: 10.1002/app.46056.
19. VIGANI, Barbara, ROSSI, Silvia, SANDRI, Giuseppina, BONFERONI, Maria Cristina, MILANESI, Giulia, BRUNI, Giovanna, FERRARI, Franca. Coated electrospun alginate-containing fibers as novel delivery system for regenerative purposes. *International Journal of Nanomedicine*, 2018, **13**, 6531−6550, doi: 10.2147/IJN.S175069.
20. ZINE, Rashtrapal, SINHA, Mukty. Nanofibrous poly(3-hydroxybutyrate-co-3-hydroxyvalerate)/collagen/graphene oxide scaffolds for wound coverage. *Materials Science & Engineering C, Materials for Biological Applications*, 2017, **80**, 129−134, doi: 10.1016/j.msec.2017.05.138.
21. CHARERNSRIWILAIWAT, Natthan, ROJANARATA, Theerasak, NGAWHIRUNPAT, Tanasait, OPANASOPIT, Praneet. Aligned electrospun polyvinyl pyrrolidone/poly epsilon-caprolactone blend nanofibrous mats for tissue engineering. *International Journal of Nanoscience*, 2016, **15**(1−2), 1650005, doi: 10.1142/S0219581X16500058.
22. OKTAY, Burcu, KAYAMAN-APOHAN, Nilhan, ERDEM-KURUCU, Serap, SÜLEYMANOGLU, Mediha. Fabrication of collagen immobilized electrospun poly(vinyl alcohol) scaffolds. *Polymers for Advanced Technologies*, 2015, **26**(8), 978−987, doi: 10.1002/pat.3512.
23. CHEN, Honglin, HUANG, Jin, YU, Jiahui, LIU, Shiyuan, GU, Ping. Electrospun chitosan-graft-poly(ε-caprolactone)/poly(ε-caprolactone) cationic nanofibrous mats as potential scaffolds for skin tissue engineering. *International Journal of Biological Macromolecules*, 2011, **48**(1), 13−19, doi: 10.1016/j.ijbiomac.2010.09.019.
24. KLINKHAMMER, Kristina, SEILER, Nadine, GRAFAHREND, Dirk, GERARDO-NAVA, José, MEY, Jörg, BROOK, Gary A., MÖLLER, Martin, DALTON, Paul D., KLEE, Doris. Deposition of electrospun fibers on reactive substrates for *In Vitro* investigations. *Tissue Engineering: Part C*, 2009, **15**(1), 77−85, doi: 10.1089/ten.tec.2008.0324.
25. CASTAGNA, Rosella, TUNESI, Marta, SAGLIO, B., DELLA PINA, Cristina, SIRONI, Annalisa, ALBANI, Diego, BERTARELLI, C., FALLETTA, E. Ultrathin electrospun PANi nanofibers for neuronal tissue engineering. *Journal of Applied Polymer Science*, 2016, **133**(35), 43885, doi: 10.1002/app.43885.
26. ARNAL-PASTOR, M., MARTÍNEZ RAMOS, C., PÉREZ GARNÉS, M., MONLEÓN PRADAS, M., VALLÉS LLUCH, A. Electrospun adherent-antiadherent bilayered membranes based

on cross-linked hyaluronic acid for advanced tissue engineering applications. *Materials Science and Engineering: C, Materials for Biological Applications*, 2013, **33**(7), 4086–4093, doi: 10.1016/j.msec.2013.05.058.

27. FAN, Lin-peng, ZHANG, Kui-hua, SHENG, Xiao-yue, WU, Chun-chen, LI, Jun, MO, Xiu-mei, WANG, Hong-sheng. Electrospinning and post-spin treatment of regenerated silk fibroin nanofibers. In *International Forum on Biomedical Textile Materials : proceedings*. 2010, 96–100.
28. MÖLLER, Johannes, KORTE, Katrin, PÖRTNER, Ralf, ZENG, An-Ping, JANDT, Uwe. Model-based identification of cell-cycle-dependent metabolism and putative autocrine effects in antibody producing CHO cell culture. *Biotechnology and Bioengineering*, 2018, **115**(12), 2996–3008, doi: 10.1002/bit.26828.
29. KRAHN, Natalie, SPEARMAN, Maureen, MEIER, Markus, DORION-THIBAUDEAU, July, MCDOUGALL, Matthew, PATEL, Trushar R., DE CRESCENZO, Gregory, DUROCHER, Yves, STETEFELD, Jörg, BUTLER, Michael. Inhibition of glycosylation on a camelid antibody uniquely affects its FcγRI binding activity. *European Journal of Pharmaceutical Sciences*, 2017, **96**, 428–439, doi: 10.1016/j.ejps.2016.09.040.
30. WIPPERMANN, Anna, RUPP, Oliver, BRINKROLF, Karina, HOFFROGGE, Raimund, NOLL, Thomas. The DNA methylation landscape of Chinese hamster ovary (CHO) DP-12 cells. *Journal of Biotechnology*, 2015, **199**, 38–46, doi: 10.1016/j.jbiotec.2015.02.014.
31. HAREDY, Ahmad M., NISHIZAWA, Akitoshi, HONDA, Kohsuke, OHYA, Tomoshi, PHTAKE, Hisao, OMASA, Takeshi. Improved antibody production in Chinese hamster ovary cells by ATF4 overexpression. *Cytotechnology*, 2013, **65**(6), 993–1002, doi: 10.1007%2Fs10616-013-9631-x.
32. RICHTER, Katharina N., REVELO, Natalia H., SEITZ, Katharina J., HELM, Marin S., SARKAR, Deblina, SALEEB, Rebecca S., D'ESTE, Elisa, EBERLE, Jessica, WAGNER, Eva, VOGL, Christian, LAZARO, Diana F., RICHTER, Frank, COY-VERGARA, Javier, COCEANO, Giovanna, BOYDEN, Edward S., DUNCAN, Rory R., HELL, Stefan W., LAUTERBACH, Marcel A., LEHNART, Stephan E., MOSER, Tobias, OUTEIRO, Tiago F., REHLING, Peter, SCHWAPPACH, Blanche, TESTA, Ilaria, ZAPIEC, Bolek, RIZZOLI, Silvio O. Glyoxal as an alternative fixative to formaldehyde in immunostaining and super-resolution microscopy. *The EMBO Journal*, 2018, **37**(1), 139–159, doi: 10.15252/embj.201695709.
33. MICHON, C., CUVELIER, G., RELKIN, P., LAUNAY, B. Influence of thermal history on the stability of gelatin gels. *International Journal of Biological Macromolecules*, 1997, **20**(4), 259–264, doi: 10.1016/S0141-8130(97)00024-X.

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Review of Possible Applications of Nanofibrous Mats for Wound Dressings

Pregled načinov uporabe nanovlaknastih kopren pri oblogah za rane

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Abstract

Skin is an important part of the human body. Its function is to control the body's homeostasis mechanism. If a skin injury occurs, it is of utmost importance to heal the skin as soon as possible. The currently available medical treatment system, however, has limited effectiveness on the regeneration of the structure and function of the injured skin, potentially causing wound infections and dehydration. The corresponding impact on the healing process may in the worst case also be fatal. To overcome these problems in wound dressing materials, nanofibrous mats are excellent candidates for wound treatment and management. Such wound dressings can be found in biomedical applications not only in drug delivery, but also as antibacterial and antimicrobial materials, and as materials for the regeneration and repair of tissue or organs. The large surface-area-to-volume ratio is one of the unique properties of nanofibrous mats. This paper gives a brief overview of possible materials and applications of nanofibrous mats for wound dressing.
Keywords: wound dressing, electrospinning, drug delivery, nanofibrous mats

Izvleček

Koža je pomemben del človeškega telesa. Njena naloga je nadziranje mehanizma homeostaze človeškega organizma. Če se koža poškoduje, je zelo pomembno, da jo čim prej zdravimo. Obstoječi sistem zdravljenja ne zagotavlja učinkovite obnove strukture in funkcije poškodovane kože, kar lahko vodi v okužbe ran in dehidracije, ki je lahko v najslabšem primeru tudi usodna. Za odpravo omenjenih težav pri sodobnih oblogah za rane so nanovlaknaste koprene odlična možnost za zdravljenje in oskrbo ran. Takšne nanovlaknaste koprene se lahko uporabljajo tudi v biomedicinske namene, ne le kot transdermalni obliži, temveč tudi kot protibakterijska in protimikrobna sredstva ter kot materiali za regeneracijo in obnovo tkiv ali organov. Ena od edinstvenih lastnosti nanovlaknastih kopren je njihovo veliko razmerje med površino in prostornino. V članku je podan kratek pregled materialov in možnosti uporabe nanovlaknastih kopren pri oblogah za rane.
Ključne besede: gaza, elektropredenje, doziranje zdravil, nanovlaknaste koprene

1 Introduction

The normal time for the wound healing process is about 2–3 days to some months, depending on the depth of the wound and the chronic condition. The healing of chronic wounds can take from a few months to several years. The classic wound dressing often has a poor fit; it is stiff and relatively hard, whereas wound dressings from nanofibrous mats are extremely thin and flexible. This type of nanofibrous mats has a breathable and water-absorbing effect, and can perfectly adapt to the wound geometry due to its high flexibility and soft surface wound dressing.
The process of modern drug delivery faces challenges, e.g. low solubility, bioavailability or targeted delivery of drugs with limited duration. Electrospun

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nanofibrous mats can overcome these problems [1, 2]. Their high surface-to-volume ratio enables improved interactions with the environment, making them promising for wound care, drug delivery and biotechnology applications. Nanofibres can thus be used for biomedical applications such as tissue engineering, wound healing processes and targeted drug delivery systems [3–9].

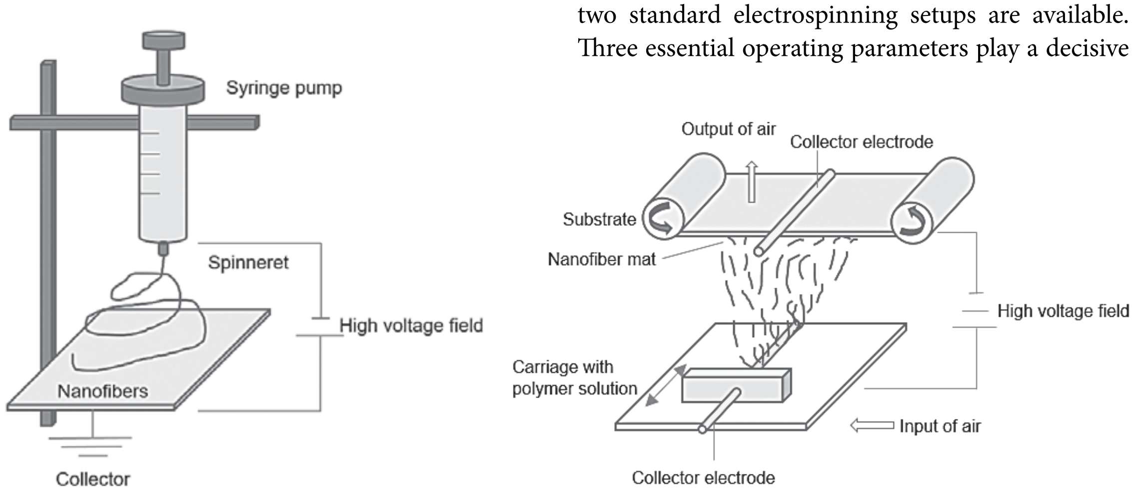
According to the results of several research groups, nanofibrous mats have the ability to absorb large concentrations of wound exudates without causing infections, and release anti-microbial and anti-inflammatory agents. Nanofibrous mats have been shown to be ideal candidates for modern and efficient wound treatment, and wound care. Being produced effectively and inexpensively in an electrospinning process, they offer a multi-promising strategy for modern wound treatment [10–13].

Nanofibres can be electrospun from natural or synthetic polymers such as polysaccharides, collagen, keratin, silk, tubulin, actin, cellulose, polyacrylonitrile (PAN), poly(lactic acid) (PLA), poly(L-lactic acid) (PLLA), acrylonitrile butadiene styrene (ABS), poly(lactic-co-glycolic acid) (PLGA), polyurethane (PU), polyvinyl alcohol (PVA), polycaprolactone (PCL), polymethyl methacraylate (PMMA), chitosan, fibrin, poly(ethylene glycol) (PEG), gelatine, casein and alginate. These and many other polymers are known in tissue engineering and are applicable in wound dressing [14–25].

2 Electrospinning techniques

Electrospinning is a technology which can be used to produce continuous ultrathin nanoscale fibres or fibre mats composed of fibres with the diameters in nanometre range [26–31]. Ultrathin fibres can be produced easily using this technology from multitude of materials, e.g. polymers, polymer composites, inorganic [32] or inorganic/organic [33] materials, or even ceramics [34]. These types of nanofibres are especially useful in the applications which necessitate large surface areas, such as promotion of cell growth in biomedical applications, catalysers, novel filter materials, medical wound dressings etc. [35–37].

Electrospinning processes can be performed in two slightly different ways, i.e. using needle-based or needleless electrospinning techniques (Figure 1). Electrospinning with a needle is a simple process which depends on a high voltage power supply with adjustable control, a polymer solution reservoir (e.g. a syringe with a small diameter needle) with or without a control pump and a metal collecting screen. The spinnable polymeric solution is put into a reservoir with a metal needle or tip and connected to a power supply, enabling the formation of a charged polymer jet. The conductive collecting screen the nanofibres are deposited on can either be a stationary plate or a rotating platform or substrate. The plate can be used to manufacture non-woven nanofibrous mats, while the rotating platform can be used to prepare both randomly oriented and aligned fibres. With a vertical and a horizontal orientation, two standard electrospinning setups are available. Three essential operating parameters play a decisive



a) b)

Figure 1: Basic set-up for (a) needle based and (b) needleless (Nanospider) electrospinning

role: namely the solution parameters, process parameters and environmental parameters [38, 39].

Needleless electrospinning is a technical process that allows electrospinning of nanofibres directly from an open liquid surface in a self-organized way. The fibre quality and productivity of spinnerets play the most important roles in needleless electrospinning. These spinnerets are connected with a high voltage power supply and a dosing unit for the spinning solution. Spinnerets for needleless electrospinning can be divided into two types, i.e. rotating or stationary spinnerets according to the working states. The rotating spinnerets can transfer mechanical vibration to the polymer solution, which results in establishing jets, mostly working continuously. An auxiliary force (e.g. a magnetic field, gravity or gas bubbles) is mostly used to establish a stationary spinneret in the electrospinning process.

Separated solution containers are used for the spinning solutions for roller and cone electrospinning. The whole process can be described by the following four steps: first, a thin layer of a polymer solution is set up on the spinneret surface which is immersed in the solution and rotated, and then, the rotation helps to create conical spikes on the solution surface. After that, by applying high voltage, the spikes concentrate the electric forces to create Taylor cones. Finally, jets spread out of the Taylor cones and produce fibres [40–42].

Especially "green" electrospinning, which avoids dangerous solvents, is of high interest in research nowadays. To prepare such nanofibrous mats, different (bio-)polymers can be electrospun from aqueous or other non-toxic solutions.

3 Electrospinnable polymer materials for wound dressing applications

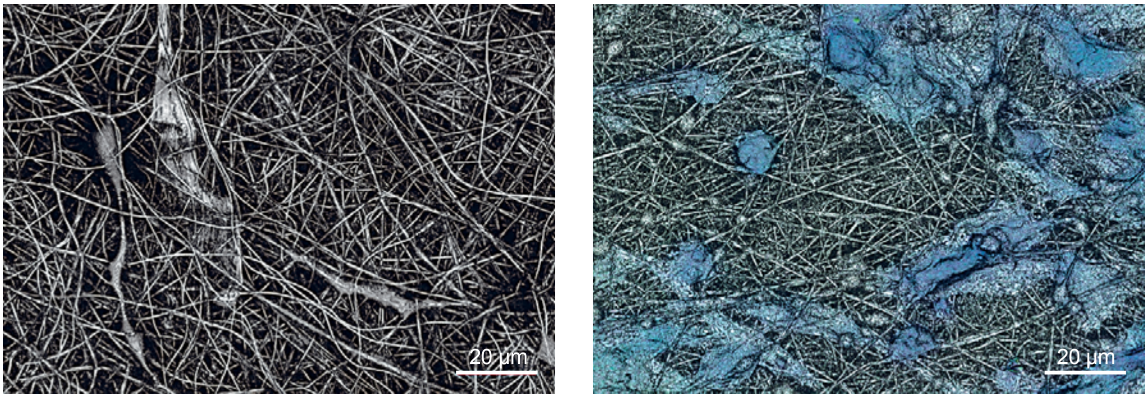
Frequently used polymers which are spinnable from non-toxic or low-toxic solvents are, for example, polyacrylonitrile (PAN, spinnable from dimethyl sulfoxide, DMSO) and poly(ethylene glycol) (PEG, spinnable from water) [43–45]. PEO and PVA are often used as the spinning agent for materials which cannot form fibres solely [46].

There are some other water-soluble polymers which have additionally interesting specific properties. Poloxamers (poly(oxyethylene-b-oxypropylene-b-oxyethylene)) can be used in blends with other polymers for drug delivery, skin tissue engineering or wound healing [47].

Dextran (carbohydrate gum formed by the fermentation of sugars and consisting of polymers of glucose) can be used for drug delivery in wound dressings or electrochemical applications in different types of blends [48]. PAN, on the other hand, is often applied for electrospinning as a precursor to produce carbon nanofibrous mats [49, 50].

Blends of different polymers are often used to produce multi-material nanofibrous mats [51] with new properties. Blending PAN with cellulose acetate can be used to increase the absorption properties of activated carbon nanofibres [52]. PAN/gelatine blends can be used for the promotion of cell growth (Figure 2) [53–55].

In bio-medicine and bio-technology, chitosan and sodium alginate have good biocompatible and



a) b)

Figure 2: Confocal laser scanning microscope (CLSM) images of (a) PAN/gelatine nanofibrous mat and (b) CHO-DP12 (Chinese hamster ovary) cells on PAN/gelatine nanofibrous mat, coloured with methylene blue on scale bar indicates 20 µm

non-toxic features, and are both widely applicable in the medical sector [56–59]. Moreover, chitosan/polyaniline composite nanofibrous mats have shown anti-bacterial properties and were found to be capable of accelerating wound healing processes [60].

PEO blended with alginate was used to prepare scaffolds by electrospinning to support human dermal fibroblast cell attachment. Nanofibre scaffolds were found to promote tissue cell adhesion and enable encapsulation of drugs [61, 62].

Chronic wound care products were improved using chitosan (PEO)/silica [73] and polyvinyl alcohol (PVA) blended with chitosan. Similarly, PVA/chitosan nanofibres, as well as collagen/PEO wound dressings were shown to have high moisture vapour transmission characteristics, good antimicrobial function and no cytotoxic effects [64–66].

Generally, nanofibrous mats can serve as a base for therapeutic agents or can accelerate chronic wound healing processes [67, 68]. A new generation of wound dressing can also be produced by electrospinning materials with high moisture absorption and anti-bacterial effects, including elements like zinc or copper alginate. These types of wound dressings contain bioactive elements, such as antimicrobial, anti-bacterial and anti-inflammatory agents, which can be released to wounds to improve their healing process [69]. Alternatively, it is even possible to electrospin fibres including commensal bacteria for medical purposes [70].

PVA/BS nanofibres have shown large potential for drug delivery, tissue engineering and tissue repair substitute properties in wound dressing [71]. PU/chitosan has been examined as well, showing promising features for wound dressing applications similar to many other biopolymer blends, e.g. blends with starch or silk [72–75].

One of the most sufficient biodegradable substances in nature is cellulose, which is widely applicable in the electrospun nanofibrous mats production [76–78]. It can be produced from certain bacterial species by fermentation. However, it is traditionally extracted from plants. Bacterial cellulose (BC) is extracted mainly from microorganisms belonging to the genera *Gluconacetobacter*. BC is widely used in biomedical applications, e.g. in drug delivery and tissue engineering [79]. It can be used to decrease pain and accelerate granulation, supporting a perfect wound healing process. It is also useful in the creation of a moist environment at the wound area and absorption of exudates. Furthermore, it can prevent microbial infections [80].

Bacterial cellulose-alginate nanocomposites were successfully produced by nanotechnology and they showed excellent antibacterial activity [81, 82]. The synthesis of BC/chitosan or chitosan/gelatine composites with high mechanical reliability and antibacterial activity was investigated by different research groups [83–87]. Similarly, chitosan blended with metallic nanoparticles has an effect on the microbial activity and wound healing [98].

The reductions of inflammatory cells and mostly closed capillary lumens have been investigated by diverse research groups, using silver nanoparticles in diverse polymer matrices [89–97].

Another investigation showed strong antibacterial and anti-inflammatory characteristics of silver nanoparticles [98]. Co-electrospinning of polyurethane and keratin which can be extracted, e.g. from human hair and fixed with silver nanoparticles, results in PU/keratin/Ag composite mats of nanofibres. These nanofibrous mats showed very good cell viability and antibacterial properties, and were thus able to promote wound healing [99]. Similarly, PU or nylon nanofibres with silver nanoparticles showed excellent antimicrobial properties [100].

Polyurethane-cellulose acetate-zein composite nanofibrous mats were found suitable for drug delivery and to have good antibacterial bio-active wound recovery characteristics [101].

Polylactic acid (PLA) nanofibres with Fe_3O_4-COOH have strong antibacterial and drug delivery activities for wound dressings and other biomedical applications [102]. PLA/CNC/PEG composite nanofibres showed therapeutic drug release properties and allowed for controlling long-time drug delivery in wound dressings [103]. Spirulina extract-alginate PCL and PCL-gelatine nanofibres were also found to show excellent wound care properties, especially for tissue regeneration [104–106].

Collagen is a widely used natural polymer substance for biomedical applications [107, 108]. It has gained broad clinical and consumer adoption as a secure material. To architecturally imitate the skin structure, nonwoven nanofibrous mats from collagen can be applied in wound healing processes which are typically produced by electrospinning. As a major fibrous protein in the extracellular matrix (ECM), collagen plays an important role in maintaining the biological and structural integrity of ECM [109, 110].

For the cell attachment, proliferation and differentiation, nonwoven collagen nanofibrous mats are of utmost importance. Moreover, these collagen nanofibrous mats are designed to induce platelet adhesion and aggregation to increase the congealing, which is favourable in wound dressing applications for the improvement of cell adhesion and proliferation [111].
Carboxymethylcellulose (CMC)/dextran hydrogels were activated with a gallium bio-glass and can be applied to reduce cancer cell viability particularly for high Ga contents in the bio-glass. CMC hydro gels cross-linked with oxidized dextran or alginate/CMC were found to significantly support the wound healing and skin regeneration [112].

4 Conclusion

A remarkable improvement has been gained in the development of therapeutic approaches to be used in the treatment of chronic wounds. Among the developed types of wound dressings, electrospun nanofibres are taken into consideration as one of the most effective wound dressing materials for the near future. They show a high surface area to volume ratio as well as a porous structure that improves homeostasis, prevents infections, absorbs exudates, enables gas permeability and cell adhesion, migration, proliferation and properly targeted drug delivery.
Several functionalization methods can be used to improve the surface properties of nanofibres or to produce nanofibres for carrier-based drug delivery, e.g. with blending electrospinnable polymers with diverse nanoparticles. Combining the intrinsic properties of diverse (bio)polymers with additional functions added in this way, electrospun nanofibrous mats belong to the most promising candidates for improved wound management.

References

1. PAL, Dan B, SRIVASTAVA, Pratap, MISHRA, A., GIRI, Deen D., SRIVASTAVA, Kumer R., SINGH, Prabht K., AWASHTHI, S., KUMER, Lata, MISHRA, Pradeep K. Synthesis and characterization of bio-composite nanofiber for controlled drug release. *Journal of Environmental Chemical Engineering*, 2017, **5**(6), 5843–5849, doi: 10.1016/j.jece.2017.11.020.
2. PAPA, Antonio, GUARINO, Vincenzo, CIRILLO, Valentina, OLIVIERO, Olimpia, AMBROSIO, Luigi. Optimization of bicomponent electrospun fibers for therapeutic use: Post-treatments to improve chemical and biological stability. *Journal of Functional Biomaterials*, 2017, **8**(4), 47, doi: 10.3390/jfb8040047.
3. PORNPITCHANARONG, Chayakarn, ROJANARATA, Theerasak, OPANASOPIT, Praneet, PATROJANASOPHON, Prasopchai, NGAWHIRUNPAT, Tanasait. Synthesis of *N*-vinylpyrrolidone/acrylic acid nanoparticles for drug delivery: Method optimization. *MATEC Web of Conferences*, 2018, **192**, 01020, doi: 10.1051/matecconf/201819201020.
4. GUMRAH DUMANLI, Ahu. Nanocellulose and its composites for biomedical applications. *Current Medicinal Chemistry*, 2014, **24**(5), 512–528, doi: 10.2174/0929867323666161014124008.
5. MCNAMARA, Karrina, TOFAI, Syed A. M. Nanoparticles in biomedical applications. *Advances in Physics: X*, 2016, **2**(1), 54–88, doi: 10.1080/23746149.2016.1254570.
6. RAMOS, Ana P., CRUZ, Marcos A. E., TOVANI, Camila B., CIANCAGLINI, Pietro. Biomedical applications of nanotechnology. *Biophysical Reviews*, 2017, **9**(2), 79–89, doi: 10.1007/s12551-016-0246-2.
7. SADEGHI, Amin, PEZESHKI-MODARESS, Mohamad, ZANDI, Mojgan. Electrospun polyvinyl alcohol/gelatin/chondroitin sulfate nanofibrous scaffold: Fabrication and in vitro evaluation. *International Journal of Biological Macromolecules*, 2018, **114**, 1248–1256, doi: 10.1016/j.ijbiomac.2018.04.002.
8. MALEKNIA, Laleh, DILAMIAN, Mandana, PILEHROOD, Mohammad Kazemi, SADEGHI-ALIABADI, Hojjat, HEKMATI, Amir Houshang. Preparation, process optimization and characterization of core-shell polyurethane/chitosan nanofibers as a potential platform for bioactive scaffolds. *Research in Pharmaceutical Sciences*, 2018, **13**(3), 273–282, doi: 10.4103/1735-5362.228957.
9. BALOGH, Weiser D., NÉMETH, Csaba, ENDER, Ferenc, GYARMATI, Benjámin S., SZILÁGYI, András F., POPPE, László. Electrospun nanofibers for entrapment of biomolecules. In *Electrospinning method used to create functional nanocomposites films*. Rijeka : InTech, 2018, pp. 135–147.

10. GROSSERHODE, Christina, WEHLAGE, Daria, GROTHE, Timo, GRIMMELSMANN, Nils, FUCHS, Sandra, HARTMANN, Jessica, MAZUR, Patrycja, RESCHKE, Vanessa, SIEMENS, Helena, RATTENHOLL, Anke, HOMBURG, Sarah Vanessa, EHRMANN, Andrea. Investigation of microalgae growth on electrospun nanofiber mats. *AIMS Bioengineering*, 2017, **4**, 376–385, doi: 10.3934/bioeng.2017.3.376.
11. AL-ENIZI, Abdullah M., ZAGHO, Moustafa M., ELZATAHRY, Ahmed A. Polymer-based electrospun nanofibers for biomedical applications. *Nanomaterials*, 2018, **8**(4), 259, doi: 10.3390/nano8040259.
12. PREEM, Liis, KOGERMANN, Karin. Electrospun antimicrobial wound dressings: novel strategies to fight against wound infections. In *Recent Clinical Techniques, Results, and Research in Wounds*. Cham : Springer, 2018, pp. 1−41, doi: 10.1007/15695_2018_133.
13. SELVARAJ, Anantha S., RAJENDRAN, Mala. Antimicrobial nanomaterials for wound dressings. In *Nanomedicine and tissue engineering: State of the art and recent trends.* Edited by K. Nandakumar, A. Robin, S. Oluwatobi Oluwafemi, K. S. Joshy, T. Sabu. 1st edition. Boca Raton : CRC Press, Taylor & Francis Group, 2016, pp. 435−492.
14. VEGA-CÁZAREZ, Claudia A., SÁNCHEZ-MACHADO, Dalia I., LÓPEZ-CERVANTES, Jaime. Overview of electrospinned chitosan nanofiber composites for wound dressings. In *Chitin-chitosan – Myriad Functionalities in Science and Technology*. Edited by Rajendra Dongre. Reka : IntechOpen, 2016, pp. 157−181, doi: 10.5772/intechopen.76037.
15. KHORSAND-GHAYENI, Mohammad, SADEGHI, Alireza, NOKHASTEH, Samira, MOLAVI, A. Mahdi. Collagen modified PLGA nanofibers as wound-dressing. In *6th International Conference on Nanostructures (ICNS6)* : proceedings. 2016, 7−10.
16. RAMÍREZ, Cedillo, E., ORTEGA, Lara W., RODRÍGUEZ, C. A., ROCHA, Refugio, M. D. Electrospinning PCL nanofibers with ceramic nanoparticles for wound dressing. In *XXXIII Congreso Annual de la Sociedad Espanolo de Ingeniería Biomédica : proceedings.* Madrid, 2015, November 4−6, pp. 362−365.
17. FELGUEIRAS, Helena, AMORIM, Maria T. P. Functionalization of electrospun polymeric wound dressings with antimicrobial peptides. *Colloids and Surfaces B: Biointerfaces*, 2015, **156**, 133−148, doi: 10.1016/j.colsurfb.2017.05.001.
18. ZAHEDI, Payam, REZAEIAN, Iraj, RANAEI-SIADAT, Seyed-Omid, JAFARI, Seyed-Hassan, SUPAPHOL, Pitt. A review on wound dressings with an emphasis on electrospun nanofibrous polymeric bandages. *Polymers Advance Technologies*, 2009, **21**(2), 77−95, doi: 10.1002/pat.1625.
19. GOH, Yi-Fan, SHAKIR, Imran, HUSSAIN, Rafaqat. Electrospun fibers for tissue engineering, drug delivery, and wound dressing. *Journal of Materials Science*, 2013, **48**(8), 3027−3054, doi: 10.1007/s10853-013-7145-8.
20. MALA, Rajendran, RUBY, Celsia A. S. Influence of solution and process parameters on the fabrication of e-spun nano fiber for wound healing: A review. *Recent Patents on Nanomedicine*, 2014, **4**(2), 102−115, doi: 10.2174/1877912304666141009230331.
21. SUWANTONG, Orawan, PANKONGADISAK, Porntipa, DEACHATHAI, Suwanna, SUPAPHOL, Pitt. Electrospun poly(L-lactic acid) fiber mats containing crude Garcinia mangostana extracts for use as wound dressings. *Polymer Bulletin*, 2014, **71**(4), 925−949, doi: 10.1007/s00289-014-1102-9.
22. AUGUSTINE, Robin, KALARIKKAL, Nandakumar, THOMAS, Sabu. Electrospun PCL membranes incorporated with biosynthesized silver nanoparticles as antibacterial wound dressings. *Applied Nanosc*ience, 2016, **6**(3), 337−344, doi: 10.1007/s13204-015-0439-1.
23. MIOTKE, Marta, STRANKOWSKA, Justyna, KWELA, J., STRANKOWSKI, Michal, PISZCZYK, Lukasz, JÓZEFOWICZ, Marek, ´and GAZDA, M. Nanosize effect of clay mineral nanoparticles on the drug diffusion processes in polyurethane nanocomposite hydrogels. *European Physical Journal Plus*, 2017, **132**, 401, doi: 10.1140/epjp/i2017-11708-1.
24. LI, Rui, CHENG, Zhiquiang, WEN, Ruicheng, ZHAO, Xiaodong, YU, Xiaobin, SUN, Lin, ZHANG, Yingying, HAN, Zhiyuan, YUAN, Yafeng, KANG, Lijuan. Novel SA@Ca^{2+}/RCSPs core–shell structure nanofibers by electrospinning for wound dressings. *RSC Adv*ances, 2018, **8**, 15558−15566, doi: 10.1039/c8ra00784e.
25. MIGUEL, Sónia P., RIBEIRO, Maximiano P., COUTINHO, Paula, CORREIA, Ilídio J. Electrospun

polycaprolactone/*Aloe Vera*_chitosan nanofibrous asymmetric membranes aimed for wound healing applications. *Polymers*, 2017, **9**(5), 183, doi: 10.3390/polym9050183.

26. CHENG, Huiling, YANG, Xiaoye, CHE, Xin, YANG, Mingshi, ZHAI, Guangxi. Biomedical application and controlled drug release of electrospun fibrous materials. *Materials Science and Engineering C*, 2018, **90**, 7502−763, doi: 10.1016/j.msec.2018.05.007.
27. DIAS, Juliana R., DOS SANTOS, Cyril, HORTA, Joao, GRANJA, Pedro Lopes, BÁRTOLO, Paulo Jorge. A new design of an electrospinning apparatus for tissue engineering applications. *International Journal of Bioprinting*, 2017, **3**(2), 1−9, doi: 10.18063/IJB.2017.02.002.
28. KOMUR, Baran, BAYRAK, Fatih, EKREN, Nazmin, EROGLU, Mehmet S, OKTAR, Faik N., SINIRLIOGLU, Zeynep A., YUCEL, Sevil, GULER, Onder, GUNDUZ, Oguhzan. Starch/PCL composite nanofibers by coaxial electrospinning technique for biomedical applications. *BioMedical Engineering OnLine*, 2017, **16**, 40, doi: 10.1186/s12938-017-0334-y.
29. GRANDCOLAS, Mathieu, SUNDE, Tor Olav, PILZ, Monika, SIMON, Christian, SCHMID, Ruth, JOHNSEN, Heidi. Needleless electrospun nanofibers containing microcapsules: a methodology for self-supported microcontainers. *Internatinal Journal of Engineering Research and Application*, 2017, **7**(6), 100−104, doi: 10.9790/9622-070601100104.
30. AGARWAL, Seema, GREINER, Andreas, BURGARD, Matthias, WENDROFF, Joachim H. *Electrospinning*. Berlin : De Gruyter, 2016, **3**(11), 033180-6.
31. RAMAKRISNA, Seeram, FUJIHARA, Kazutoshi, TEO, Wee-Eong, LIM, Teik-Cheng, MA, Zuwei. *Introduction to Electrospinning and Nanofibers*. World Scientific, 2005, **981**(256), pp. 415−2.
32. MAHLTIG, Boris, TEXTOR, T. *Nanosols and Textiles*. World Scientific, 2008, **13,** doi: 10.1142/6961.
33. TOSKA, Georgios, CHERIF, Chokri, HUND, Ralf, LAOURINE, Ezzeddine, MAHLTIG, Boris, FAHMI, Amir. Inorganic/organic (SiO2)/PEO hybrid electrospun nanofibers produced from a modified sol and their surface modification possibilities**.** *ACS Applied Materials & Interfaces,* 2011, **3**(9), 3673−81, doi: 10.1021/am200858s.
34. WU, N., JU, Su, WANG, Yinge, CHEN, Ding. Fabrication of Ni@SiC composite nanofibers by electrospinning and autocatalytic electroless plating techniques. *Results in Physics*, 2019, **12**, 853−858, doi: 10.1016/j.rinp.2018.12.051.
35. KUO, Ting-Yun, LIN, Che-Min, HUNG, Shih-Chieh, HSIEN, Tzu-Yang, WANG, MING, Da, HSEIN, Hsyue-Jen. Incorporation and selective removal of space-forming nanofibers to enhance the permeability of cytocompatibility nanofiber membranes for better cell growth. *Journal of the Taiwan Institute of Chemical Engineering*, 2018, **91**, 146−154, doi: 10.1016/j.jtice.2018.06.011.
36. YANG, L., HOU, L. R., ZHANG, Y. W., YUAN, Changzhou. Facile synthesis of mesoporous carbon nanofibres towards high-performance electrochemical capacitors. *Materials Letters,* 2013, **97**, 97−99, doi: 10.1016/j.matlet.2012.12.018.
37. ZHANG, Shichao, RIND, Nadir Ali, TANG, Ning, LIU, Hui, YIU, Xia, YU, Jianyong, DING, Bin. Electrospun nanofibers for air filtration. In *Micro and nano technologies, electrospinning, nanofabrication and applications*. William Andrew Publishing, 2019, pp. 365−389, doi: 10.1016/B978-0-323-51270-1.00012-1.
38. ZABAR, Nabeel, AL-HAZEEM, Abed. Nanofibers and electrospinning method. *Novel Nanomaterials - Synthesis and Applications,* 2016, **11**, 193−208, doi: 10.5772/intechopen.72060.
39. KUREČIČ, Manja, SMOLE, Majda Sfiligoj. Electrospinning: Nanofibre production method. *Tekstilec*, 2013, **56,** 4−12, doi: 10.14502/Tekstilec2013.56.4-12.
40. NIU, Haitao, LIN, Tong. Fiber generators in needleless electrospinning. *Journal of Nanomaterials,* 2012, **2012**, doi: 10.1155/2012/725950.
41. VYSLUZILOVA, Lucie, BUZGO, Matej, POKORNY, Pavel, CHVOJKA, Jiří MIKOVA, Andrea, RAMPICHOVA, Michala, KULA, Jiří, PEJCHAR, Karel, BILEK, Martin, LUKAS, David, AMLER, Evžen. Needleless coaxial electrospinning: A novel approach to mass production of coaxial nanofibers. *International Journal of Pharmaceutics,* 2017, **516**(1−2), 293−300, doi: 10.1016/j.ijpharm.2016.11.034.
42. KOSTAKOVA, Eva, MESZAROS, Laszlo, GREGR, Jan. Composite nanofibers produced by

modified needleless electrospinning. *Materials Letters,* 2009**, 63**(28), 2419–2422, doi: 10.1016/j.matlet.2009.08.014.

43. DÍAZ, Angélica, DEL, Valle L. J., RODRIGO, Noel, CASAS, Maria T., CHUMBURIDZE, Georg, KATSARAVA, Ramaz, PUIGGALÍ, Jordi. Antimicrobial activity of poly(ester urea) electrospun fibers loaded with bacteriophages. *Fibers*, 2018, **6**(2), 33, doi: 10.3390/fib6020033.
44. GROTHE, Timo, BRIKMANN, Johannes, MEISSNER, Hubert, EHRMANN, Andrea. Influence of solution and spinning parameters on nanofiber mat creation of poly(ethylene oxide) by needleless electrospinning. *Materials Science (Medžiagotyra),* 2017, **23**(4), 342–349, doi: 10.5755/j01.ms.23.4.17169.
45. VAJDAI, Attila, NAGY, Zsombor K., DREDÁN, Judit, SZABÓ, Barnabás, ZELKÓ, Romána, MAROSI, György, UJHELYI, Gabriella. Correlation between the physical characteristics of aqueous PVA solutions and the average diameter of electrospun nanofibers. *Latin American Journal of Pharmacy*, 2012, **31**(10), 1513–1517.
46. SABANTINA, Lilia, MIRASOL, José R., CORDERO, Tomás, FINSTERBUSCH, Karin, EHRMANN, Andrea. Investigation of needleless electrospun PAN nanofiber mats. In *AIP Conference : proceedings.***1952**(1), 020085, doi: 10.1063/1.5032047.
47. PAN, Jian-feng, LIN, Ning-hua, SUN,Hui, XU, Feng. Preparation and characterization of electrospun PLCL/poloxamer nanofibers and dextran/gelatin hydrogels for skin tissue engineering. *Plos One,* 2014, **9**(11), 112885, doi: 10.1371/journal.pone.0112885.
48. BÖTTJER, Robin, GROTHE, Timo, WEHLAGE, Daria, EHRMANN, Andrea. Electrospraying poloxamer/(bio-)polymer blends using a needleless electrospinning machine. *Journal of Textiles and Fibrous Materials*, 2018, **1**, 1–7, doi: 10.1177/2515221117743079.
49. ZHANG, Lifeng, ABOAGYE, Alex, KELKAR, Ajit, LAI, Chuilin, FONG, Hao. A review: Carbon nanofibers from electrospun polyacrylonitrile and their applications. *Journal of Materials Science*, 2014, **49**(2), 463–480, doi: 10.1007/s10853-013-7705-y.
50. RAJZER, Izabella, KWIATKOWSKI, Ryszard, PIEKARCZK, Wojciech, BINIAS, Włodzimierz, JANICKI, Jarosław. Carbon nanofibers produced from modified electrospun PAN/hydroxyapatite precursors as scaffolds for bone tissue engineering. *Materials Science and Engineering: C,* 2012, **32**(8), 2562–2569, doi: 10.1016/j.msec.2012.07.041.
51. AGBOOLA, Oluranti S., SADIKU, Emmanuel R. Theoretical modeling of nanostructured formation in polymer blends. In *Nanostructured polymer blends.* Edited by Sabu Thomas, Robert Shanks and Sarathchandran Chandrasekharakuruo. Oxford : Elsevier, 2014, pp. 33–99.
52. WEHLAGE, Daria, BÖTTJER, Robin, GROTHE, Timo, EHRMANN, Andrea. Electrospinning water-soluble/insoluble polymer blends. *AIMS Materials Science*, 2018, **5**(2), 190–200, doi: 10.3934/matersci.2018.2.190.
53. SABANTINA, Lilia, WEHLAGE, Daria, KLÖCKER, Michaela, MAMUN, Al, GROTHE, Timo, GARCIA-MTEOS, Francisco J., RODRIGUES-MIRASOL, José CORDERO, Tomás, FINSTERBUSCH, Karin, EHRMANN, Andrea. Stabilization of electrospun PAN/gelatin nanofiber mats for carbonization. *Journal of nanomaterials,* 2018, Article ID 6131085, doi: 10.1155/2018/6131085.
54. SEMNANI, Kourosh, SHAMS-GHAHFAROKHI, Masoomeh, AFRASHI, Mehran, FAKHRALI, Aref, SEMNANI, Dariush. Antifungal activity of eugenol loaded electrospun PAN nanofiber mats against *Candida albicans*. *Current Drug Delivery*, 2018, **15**(6), 860–866, doi: 10.2174/1567201815666180226120436.
55. FAYEMI, Omolola E., EKENNIA, Anthony C., KATATA-SERU, Lebokang, EBOKAIWE, Azubuike P., IJOMONE, Omamuyovwi M., ONWUDIWE, Damia C., EBENSO, Eno E. Antimicrobial and wound healing properties of polyacrylonitrile-moringa extract nanofibers. *ACS Omega*, 2018, **3**(5), 4791–4797, doi: 10.1021/acsomega.7b01981.
56. GITO, G., ROCHMAWATI, E. Effectiveness of modern wound dressing on the growth of staphylococcus aureus bacteria. *Jurnal Keperawatan*, 2018, **9**(2), 88–99, doi: 10.22219/jk.v9i2.5160.
57. GIERSZEWSKA, Magdalena, OSTROWSKA-CZUBENKO, Jadwiga, CHRZANOWSKA, Ewelina. Characteristics of ascorbic acid release from TPP-crosslinked chitosan/alginate polyelectrolyte complex membranes. *Progress on*

Chemistry and Application of Chitin and its Derivatives, 2018, **7**, 76–87, doi: 10.15259/PCACD.23.007.
58. PÉREZ PUYANA V., JIMÉNEZ ROSADO M., ROMERO, A., GUERRERO, Antonio. Development of PVA/gelatin nanofibrous scaffolds for tissue engineering via electrospinning. *Materials Research Express*, 2018, **5**, 035401, doi: 10.1088/2053-1591/aab164.
59. ZHOU, Yingshan, LIANG, Kaili, ZHANG, Can, LI, Jun, YANG, Hongjun, LIU, Xin, YIN, Xianze, CHEN, Dongzhi, XU, Weilin, XIAO, Pu. Photocrosslinked methacrylated chitosan-based nanofibrous scaffolds as potential skin substitute. *Cellulose*, 2017, **24**(10), 4253−4262, doi: 10.1007/s10570-017-1433-4.
60. MOUTSATSOU, Panagiota, COOPMAN, Karen, GEORGIADOU, Stella. Biocompatibility assessment of conducting PANI/chitosan nanofibers for wound healing applications. *Polymers*, 2017, **9**(12), 687, doi: 10.3390/polym9120687.
61. CHARERNSRIWILAIWAT, Natthan, OPANASOPIT, Praneet, ROJANARATA, Theerasak, NGAWHIRUNPAT, Tanasait. Fabrication and characterization of chitosan-ethylenediaminetetraacetic acid/polyvinyl alcohol blend electrospun nanofibers. *Advanced Materials Research*, 2011, **194–196**, 648−651, doi: 10.4028/www.scientific.net/AMR.194-196.648.
62. JEONG, Sung In, KREBS, Melissa, BONINO, Cristopher, KHAN, Saad Arman, ALSBERG, Eben. Electrospun alginate nanofibers with controlled cell adhesion for tissue engineering. *Micromolecular Bioscience*, 2010, **10**(8), 934−943, doi: 10.1002/mabi.201000046.
63. TOSKA, Georgios, CHERIF, Chokri, HUND, Ralf, LAOURINE, Ezzeddine, MAHLTIG, Boris, FAHMI, Amir, HEINEMANN, Christiane, HANKE, Thomas. Chitosan(PEO)/silica hybrid nanofibers as a potential biomaterial for bone regeneration. *Carbohydrate polymers,* 2013, **94**(2), 713−722, doi: 10.1016/j.carbpol.2013.01.068.
64. DUBEY, Poornima, PACKIRISAMY Gopinath. PEGylated graphene oxide-based nanocomposite grafted chitosan/polyvinyl alcohol nanofiber as an advanced antibacterial wound dressing. *RSC Advances*, 2016, **6**, 69103−69116, doi: 10.1039/C6RA12192F.
65. ZHAO, Xinzhe, GAO, Jing, HU, Xingyou, GUO, Huiwen, WANG, Fujun, QIAO, Yansha, WANG, Lu. Collagen/polyethylene oxide nanofibrous membranes with improved hemostasis and cytocompatibility for wound dressing. *Applied Sciences*, 2018, **8**(8), 1226, doi: 10.3390/app8081226.
66. SANCHEZ-ALVARADO, Diana I., GUZMÁN-PANTOJA, Javier, PRAMO-GARCIA, Ulises, MACIEL-CERDA, Alfredo, MARTÍNEZ-OROZCO, Reinaldo D., VERA-GRAZIANO, Ricardo. Morphological study of chitosan/poly (vinyl alcohol) nanofibers prepared by electrospinning, collected on reticulated vitreous carbon. *International Journal of Molecular Sciences*, 2018, **19**(6), e1718, doi: 10.3390/ijms19061718.
67. GIANINO, Elizabeth, MILLER, Craig, GILMORE, Jordon. Smart wound dressings for diabetic chronic wounds. *Bioengineering*, 2018, **5**(3), 51, doi: 10.20944/preprints201805.0396.v1.
68. AYTIMUR, Arda, USLU, Ibrahim. Promising materials for wound dressing: PVA/PAA/PVP electrospun nanofibers. *Polymer-Plastics Technology and Engineering*, 2014, **53**(7), 655−660, doi: 10.1080/03602559.2013.874031.
69. GONG, Ying, HAN, Guangting, ZHANG, Yuanming, PAN, Yong, LI, Xianbo, XIA, Yanzhi, WU, Yan. Antifungal activity and cytotoxicity of zinc, calcium, or copper alginate fibers. *Biological Trace Element Research*, 2012, **148**(3), 415−419, doi: 10.1007/s12011-012-9388-7.
70. KURECIC, Manja, RIJAVEC, Tomaž, HRIBERNIK, Silvo, LAPANJE, Aleš, KLEINSCHEK STANA, Karin, MAVER, Uroš. Novel electrospun fibers with incorporated commensal bacteria fr potential preventive treatment of the diabetic foot. *Nanomedicine*, 2018, **13**(13), 1583−1594, doi: 10.2217/nnm-2018-0014.
71. LIN, Jia-Horng, LU, Chao-Tsang, HU, Jin-Jin, CHEN, Yueh-Sheng, HUANG, Chen-Huang, and LOU, Ching-Wen. Property evaluation of *Bletilla striata*/polyvinyl alcohol nano fibers and composite dressings. *Journal of Nanomaterials*, 2012, **12**, Article ID 519516, doi: 10.1155/2012/519516.
72. CAI, Zeng-xiao, MO, Xiu-mei, ZHANG, Kuihua, FAN, Lin-peng, YIN, An-lin, HE, Chuanglong, WANG, Hong-sheng. Fabrication of chitosan/silk fibroin composite nanofibers for wounddressing applications. *International Journal of Molecular Sciences*, 2010, **11**(9), 3529−3539, doi: 10.3390/ijms11093529.
73. JAITURONG, Patthanakorn, SIRITHUNYALUG, Busaban, EITSAYEAM, Sukum, ASA-

WAHAME, Chawalinee, TIPDUANGTA, Prat-chaya, SIRITHUNYALUG, Jakkapan. Preparation of glutinous rice starch/polyvinyl alcohol copolymer electrospun fibers for using as a drug delivery carrier. *Asian Journal of Pharmaceutical Sciences*, 2018, **13**(3), 239–247, doi: 10.1016/j.ajps.2017.08.008.

74. ARUAN, Neni Mona, SRIYANTI, Ida, EDIKRESNHA, Dhewa, SUCIATI, Tri, MUNIR, Muhammad Miftahul, KHAIRURRIJAL. Polyvinyl alcohol/soursop leaves extract composite nanofibers synthesized using electrospinning technique and their potential as antibacterial wound dressing. *Procedia Engineering*, 2017, **170**, 31–35, doi: 10.1016/j.proeng.2017.03.006.
75. SUBTIRICA, Adriana-Ioana, BANCIU, Cristina A., CHIVU, Andreea Ana-Maria, DINCA, Laurentiu-Christian. Nanofibres made from biocompatible and biodegradable polymers, with potential application as medical textiles. *Industria textila*, 2018, **69**(1), 55–58.
76. LIANG, Luna, HUANG, Chen, RAGAUSKAS, Arthur J. Nanocellulose-based materials for biomedical applications. *JSM Chemistry*, 2017, **5**(3), 1048.
77. TARUS, Bethwel, FADEL, Nermin, AL-OUFY, Aaffaf, EL-MESSIRY, Magdi. Effect of polymer concentration on the morphology and mechanical characteristics of electrospun cellulose acetate and poly(vinyl chloride) nanofiber mats. *Alexandria Engineering Journal*, 2016, **55**(3), 2975–2984, doi: 10.1016/j.aej.2016.04.025.
78. TRACHE, Djalal. Nanocellulose as a promising sustainable material for biomedical applications. *AIMS Materials Science*, 2018, **5**(2), 201–205, doi: 10.3934/matersci.2018.2.201.
79. MOREIRA, Susana, BEYERRA, Naisandra, JAILMA, Silva, LIMA, Almeida, ALEXANDRE, Hugo, ROCHA, Oliveira, REGINA, Silva, ALVESJR, Clodomiro, GAMA, Francisco M. BC nanofibres: *In vitro* study of genotoxicity and cell proliferation. *Texicology Letters*, 2019, **189**(3), 235−241, doi: 10.1016/j.toxlet.2009.06.849.
80. SULAEVA, Irina, HENNIGES, Ute, ROSENAU, Thomas, POTTAS, Antjie. Bacterial cellulose as a material for wound treatment: Properties and modifications. *Biotechnology Advantages,* 2015, **33**(8), 1547−1571, doi: 10.1016/j.biotechadv.2015.07.009.
81. SURATAGO, Theerawat, TAOKAEW, Siriporn, KANJANAMOSIT, Nitisak, KANJANAPRAPAKUL, Kijchai, BURAPATANA, Vorakan, PHISALAPHONG, Muenduen. Development of bacterial cellulose/alginate nanocomposite membrane for separation of ethanol-water mixtures. *Journal of Industrial and Engineering Chemistry*, 2015, **32**, 305–312, doi: 10.1016/j.jiec.2015.09.004.
82. LIYASKINA, Elena V., REVIN, Victor, PARAMONOVA, E. N., REVINA, N. V., KOLESNIKOVA, S. G. Bacterial cellulose/alginate nanocomposite for antimicrobial wound dressing. In *The 2nd International Symposium on Physics, Engineering and Technologies for Biomedicine : proceedings*. 2018, **2018**, 202–211, doi: 10.18502/ken.v3i2.1814.
83. HABIBI, Sima, HAJINASROLLAH, Kiana. Electrospinning of nanofibers based on chitosan/gelatin blend for antibacterial uses. *Russian Journal of Applied Chemistry*, 2018, **91**(5), 877–881, doi: 10.1134/S1070427218050191.
84. LIYASKINA, Elena V., REVIN, Victor, PARAMONOVA, E., NAZARKINA, Maria, PESTOV, N., REVINA, N., KOLESNIKOVA, S. Nanomaterials from bacterial cellulose for antimicrobial wound dressing. *Journal of Physics Conference Series*, 2017, **784**(1), 012034, doi: 10.1088/1742-6596/784/1/012034.
85. GHARAIE, Sadaf Samimi., HABIBI, Sima, NAZOCKDAST, Hosein. Fabrication and characterization of chitosan/gelatin/thermoplastic polyurethane blend nanofibers. *Journal of Textiles and Fibrous Materials*, 2018, **1**, 1–8, doi: 10.1177/2515221118769324.
86. PEZESHKIMODARESS, Mohamad, ZANDI, Mojgan, RAJABI, Sarah. Tailoring the gelatin/chitosan electrospun scaffold for application in skin tissue engineering: an in vitro study. *Progress in Biomaterials*, 2018, **7**(3), 207–218, doi: 10.1007/s40204-018-0094-1.
87. MOHANDAS, Annapoorna, DEEPTHI, S., BISWAS, Raja, JAYAKUMAR, R. Chitosan based metallic nanocomposite scaffolds as antimicrobial wound dressings. *Bioactive Materials*, 2018, **3**(3), 267–277, doi: 10.1016/j.bioactmat.2017.11.003.
88. UTTAYARAT, Pimpon, JETAWATTANA, Suwimol, SUWANMALA, Phiriyatorn, EAMSIRI, Jarurattana, TANGTHONG, Theeranan, PONGPAT, Suchada. Antimicrobial electrospun silk

fibroin mats with silver nanoparticles for wound dressing application. *Fibers and Polymers*, 2012, **13**(8), 999–1006, doi: 10.1007/s12221-012-0999-6.

89. PÉREZDÍAZ, Mario A., SILVABERMUDEZ, Phaedra, JIMÉNEZLÓPEZ, Binisa, MARTÍNEZLÓPEZ, Valentín, MELGAREJORAMÍREZ, Yaaziel, BRENAMOLINA, Ana, IBARRA, Clemente, BAEZA, Isabel, MARTÍNEZPARDO, Maria E., REYESFRÍAS, Ma de Lourdes, MÁRQUEZGUTIÉRREZ, Erik, VELASQUILLO, Cristina, MARTÍNEZCASTAÑON, Gabriel A., MARTINEZGUTIERREZ, Fidel, SÁNCHEZSÁNCHEZ, Roberto. Silver-pig skin nanocomposites and mesenchymal stem cells: suitable antibiofilm cellular dressings for wound healing. *Journal of Nanobiotechnology*, 2018, **16**(1), 2, doi: 10.1186/s12951-017-0331-0.
90. ZHANG, Huijie, PENG, Mengxia, CHENG, Ting, ZHAO, Peng, QUI, Lipeng, ZHOU, Juan, LU, Guozhong, CHEN, Jinghua. Silver nanoparticles-doped collagen–alginate antimicrobial biocomposite as potential wound dressing. *Journal of Materials Science*, 2018, **53**(21), 14944–14952, doi: 10.1007/s10853-018-2710-9.
91. WU, Tianyi, LU, Fei, WEN, Qiuhan, YU, Kun, LU, Bitao, RONG, Bao, DAI, Fangyin, LAN, Guangqian. Novel strategy for obtaining uniformly dispersed silver nanoparticles on soluble cotton wound dressing through carboxymethylation and in-situ reduction: antimicrobial activity and histological assessment in animal model. *Cellulose*, 2018, **25**(9), 5361–5376, doi: 10.1007/s10570-018-1907-z.
92. KHAMPIENG, Thitikan, WONGKITTITHAVORN, Supisara, CHAIARWUT, Sonthaya, EKABUTR, Pongpol, PAVASANT, Prasit, SUPAPHOL, Pitt. Silver nanoparticles-based hydrogel: Characterization of material parameters for pressure ulcer dressing applications. *Journal of Drug Delivery Science and Technology*, 2017, **44**, 91–100, doi: 10.1016/j.jddst.2017.12.005.
93. LI, Qing, LU, Fei, ZHOU, Goufang, YU, Kun, LU, Bitao, XIAO, Yang, DAI, Fangying, WU, Dayang, and LAN, Guangqian. Silver inlaid with gold nanoparticle/chitosan wound dressing enhances antibacterial activity and porosity, and promotes wound healing. *Biomacromolecules*, 2017, **18**(11), 3766–3775, doi: 10.1021/acs.biomac.7b01180.
94. YU, Kun, LU, Fei, LI, Qing, CHEN, Honglei, LU, Bitao, LIU, Jiawei, LI, Zhiquan, DAI, Fangying, WU, Dayang & LAN, Guangqian. In situ assembly of Ag nanoparticles (AgNPs) on porous silkworm cocoon-based wound film: enhanced antimicrobial and wound healing activity. *Scientific Reports*, 2017, **7**, 2107, doi: 10.1038/s41598-017-02270-6.
95. GÓMEZ CHABALA, Luisa F., ECHEVERRI CUARTAS, Claudia E., LONDONO LÓPEZ, Martha E. Release behavior and antibacterial activity of chitosan/alginate blends with *Aloe vera* and silver nanoparticles. *Marine Drugs*, 2017, **15**(11), 328, doi: 10.3390/md15100328.
96. KONOP, Marek, DAMPS, Tatsiana, MISICKA, Aleksandra, RUDNICK, Lidia. Certain aspects of silver and silver nanoparticles in wound care. *Journal of Nanomaterials*, 2016, **2016**, Article ID 7614753, doi: 10.1155/2016/7614753.
97. TRA, Thanh Nhi, HO, Hieu Minh, TRAN, Minh Phuong N., DO, Bui Thuan Thien, NGUYEN, Thi Thoai Hoai, THAI, Van Phuoc, DO, Min Thai, NGUYEN, Dai Hai, VO, Van Toi, NGUYEN, Thi Hiep. Optimization and characterization of electrospun polycaprolactone coated with gelatin-silver nanoparticles for wound healing application. *Materials Science and Engineering C*, 2018, **91**, 318–329, doi: 10.1016/j.msec.2018.05.039.
98. CHEN, Jyh-Ping and CHIANG, Yun. Bioactive electrospun silver nanoparticles-containing polyurethane nanofibers as wound dressings. *Journal of Nanoscience and Nanotechnology*, 2010, **10**(11), 7560–7564, doi: 10.1166/jnn.2010.2829.
99. WANG, Yanfang, LI, Pengfei, XIANG, Ping, LU, Jueting, YUAN, Jiang, SHEN, Jian. Electrospun polyurethane/keratin/AgNP biocomposite mats for biocompatible and antibacterial wound dressings. *Journal of Materials Chemistry B*, 2016, **4**, 635–648, doi: 10.1039/C5TB02358K.
100. XU, Z., MAHALINGAM, Suntharavathanan, ROHN, Jennifer L., REN, Guogang, EDIRISINGHE, Mohan. Physio-chemical and antibacterial characteristics of pressure spun nylon nanofibres embedded with functional silver nanoparticles. *Materials Science and Engineering C*, 2015, **56**, 195–204, doi: 10.1016/j.msec.2015.06.003.

101. UNNITHAN, Afeesh Rajan, GNANASEKARAN, Gopalsamy, SATHISHKUMAR, Yesupatham, LEE, Yang Soo, KIM, Cheol Sang. Electrospun antibacterial polyurethane–cellulose acetate–zein composite mats for wound dressing. *Carbohydrate Polymers*, 2014, **102**, 884–892, doi: 10.1016/j.carbpol.2013.10.070.
102. HAN, Chao, CAI, Ning, CHAN, Vincent, LIU, Mingming, FENG, Xiaojuan, YU, Faquan. Enhanced drug delivery, mechanical properties and antimicrobial activities in poly(lactic acid) nanofiber with mesoporous Fe_3O_4-COOH nanoparticles. *Colloids and Surfaces A: Physicochemical and Engineering Aspects,* 2018, **559**, 104–114, doi: 10.1016/j.colsurfa.2018.09.012.
103. YU, Hou-Yong, WANG, Chuang, ABDALKARIM, Somia Y. H. Cellulose nanocrystals/polyethylene glycol as bifunctional reinforcing/compatibilizing agents in poly(lactic acid) nanofibers for controlling long-term in vitro drug release. *Cellulose*, 2017, **24**(10), 4461–4477, doi: 10.1007/s10570-017-1431-6.
104. CHOI, Jung Il, KIM, Min Sik, CHUN, Goo Yong, SHIN, Hwa Sung. *Spirulina* extract-impregnated alginate-PCL nanofiber wound dressing for skin regeneration. *Biotechnology and Bioprocess Engineering*, 2017, **22**(6), 679–685, doi: 10.1007/s12257-017-0329-3.
105. KIM, Min Sik, KIM, Hye Jim, JANG, Jin Yuong, SHIN, Hwa Sung. Development of coaxial alginate-PCL nanofibrous dressing for controlled release of *Spirulina* extract. *Journal of Biomaterials Science, Polymer Edition*, 2018, **29**(12),1389–1400,doi:10.1080/09205063.2018.1462931.
106. RATHER, Hilal Ahmad, THAKORE, Ria, SINGH, Ragini, JHALA, Dhwani, SINGH, Sanjay, VASITA, Rajesh. Antioxidative study of cerium oxide nanoparticle functionalized PCL-gelatin electrospun fibers for wound healing application. *Bioactive Materials*, 2017, **3**(2), 201–211, doi: 10.1016/j.bioactmat.2017.09.006.
107. TORT, Serdar, ACARTÜRK, Füsun, BESIKCI, Arzu. Evaluation of three-layered doxycycline-collagen loaded nanofiber wound dressing. *International Journal of Pharmaceutics*, 2017, **529**(1–2), 642–653, doi: 10.1016/j.ijpharm.2017.07.027.
108. DA SILVA, Cinara V., PEREIRA, Veronica de J., COSTA, G. M. N., CABRAL-ALBUQUERQUEA, Elaina. C. M., DE MELO, Vieira S., DE SOUSA, Herminio C., DIAS, Ana M. A., BRAGA, Mara E. M. Supercritical solvent impregnation/deposition of spilanthol-enriched extracts into a commercial collagen/cellulose-based wound dressing. *The Journal of Supercritical Fluids*, 2018, **133**(1), 503–511, doi: 10.1016/j.supflu.2017.11.028.
109. GARG, Sweta, GARG, Ashish, SHUKLA, Ajay, DEV, Suresh Kumar, KUMAR, Manish. A review on nano-therapeutic drug delivery carriers for effective wound treatment strategies. *Asian Journal of Pharmacy and Pharmacology*, 2018, **4**(2), 90–101, doi: 10.31024/ajpp.2018.4.2.1.
110. DIAS, Juliana R., SILVA-BAPTISTA, Sara, OLIVEIRA, Carla, SOUSA, Aureliana, OLIVEIRA, A. L., BÁRTOLO, Paulo, GRANJA, Pedro L. *In situ* crosslinked electrospun gelatin nanofibers for skin regeneration. *European Polymer Journal*, 2017, **95**, 161–173, doi: 10.1016/j.eurpolymj.2017.08.015.
111. ZHAO, Xinzhe, GAO, Jing, HU, Xingyou, GUO, Huiwen, WANG, Fujun, QIAO, Yansha, WANG, Lu. Collagen/polyethylene oxide nanofibrous membranes with improved hemostasis and cytocompatibility for wound dressing. *Applied science,* 2018, **8**(8), 1226, doi: 10.3390/app8081226.
112. UZUN, M. Developments in nonwovens for wound dressings. In *Advances in technical nonwovens*. Edited by George Kellie. Woodhead Publishing, 2016, pp. 443–472, doi: 10.1016/B978-0-08-100575-0.00017-6.

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Mechanism of Colloidal Attachment on Textile Fibrous Media
Mehanizem koloidnega pritrjevanja na tekstilne vlaknaste medije

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Abstract
Filtration through the porous media of a granular bed is one of the oldest and most favourable particle separation techniques used universally for the treatment of water. In the case of filtration through a granular bed, all physical factors are incorporated into a single collector contact efficiency. The latter is the ratio of the rate at which particles strike the collector to the rate at which particles flow towards the collector. On the other hand, collision or attachment efficiency represents the chemical interaction between the media used and colloids, and is expressed as the ratio of the number of particles removed by the collector to the number of particle collector collisions, or the possibility that a collision in an attachment. Textile media is emerging as a substrate in deep bed filtration due to its superior performance in the removal of colloidal particles from water under higher filtration velocities compared with granular media. Reported studies relating to the effect of physicochemical factors on colloidal removal in textile fibrous media are mainly based on the experimental value of the concentration variation of colloidal particles in input and output water. Presented in this paper is a way in which colloidal filtration theory can be extended to textile filter media in order to explain the mechanism of attachment of colloids (primarily bacteria) on a textile fibrous media surface.
Keywords: textile filter, single collector contact efficiency, collision efficiency, hydrophobicity, pore size, surface charge

Povzetek
Filtracija skozi porozni medij z zrnatim slojem je ena najstarejših in najboljših tehnik ločevanja delcev, ki se uporabljajo za obdelavo vode. Pri filtraciji skozi zrnati sloj so vsi fizikalni dejavniki vključeni v učinkovitost stika z enojnim filtracijskim medijem. Ta pomeni razmerje med hitrostjo, s katero se delci nabirajo na filtracijskem mediju, in hitrostjo, s katero se delci pomikajo proti filtracijskemu mediju. Po drugi strani pa je trk oziroma učinek pritrditve kemična interakcija med uporabljenim medijem in koloidi, izražena kot razmerje med številom delcev, ki jih je medij odstranil, in številom trkov ob filtracijski medij oziroma možnostjo za takšen trk. Tekstilni medij se manifestira kot nosilec filtracijskega globinskega sloja zaradi svojih odličnih zmogljivosti pri odstranjevanju koloidnih delcev iz vode pri višjih hitrostih filtracije v primerjavi z zrnatimi mediji. Študije, ki se nanašajo na učinek fizikalno-kemijskih dejavnikov na odstranitev koloidnih delcev v tekstilnih vlaknatih medijih, temeljijo predvsem na eksperimentalni vrednosti variiranja koncentracije koloidnih delcev v vstopni in izstopni vodi. V prispevku je predstavljen način, kako lahko teorijo koloidne filtracije razširimo na tekstilne filtrne medije, da pojasnimo mehanizem pritrditve koloidov (predvsem bakterij) na tekstilno vlaknato površino.
Ključne besede: tekstilni filter, učinkovitost stika z enojnim filtracijskim medijem, učinkovitost trka, hidrofobnost, velikost por, površinski nabo

1 Introduction

Colloids are finely divided particles distributed in a dispersion medium. The diameter of particles ranges from around 10 nm to 10μm [1]. Many of these colloids (viruses, bacteria and protozoan parasites) in surface water pose a risk to public health [2]. Numerous processes are available for the removal of these colloids, which is achieved using an attachment mechanism. Filtration through porous media

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is an effective process for the removal of colloids from surface water using an attachment mechanism [3]. Significant efforts have been made by a number of researchers in the development of colloidal filtration theory (mainly sand, glass bed, etc., as mentioned in theory) based on the physicochemical interaction between colloids and media [4–6]. The main limitations in granular media are the capacity to retain colloidal particles within the pore spaces and a low filtration rate [7]. However, granular filtration theory is well developed based on the physicochemical interaction of the bed and colloidal particles. Textile materials have emerged in recent years as a substrate that can be used as filter media for the removal of colloidal particles from surface water using an attachment mechanism [8]. Superior performance in the removal of colloidal particles from water can be achieved by textile fibrous media under filtration velocities that are ten times higher than granular media [9].

There are several varieties of textile fibre available on the market that can be used as filter media. However, the efficient removal of colloidal particles from surface water using a textile filter relies heavily on the type of fibres used as filtering media. Most textile filtration research is based on the effect of the shape, size, thickness, hydrophobicity and surface charge of textile media on filtration efficiency [10]. These factors of textile fibrous media filters are similar to the physicochemical factors of granular media that serve as the basis of an attachment mechanism. A quantitative analysis of textile fibrous media may be possible by extending the physicochemical interaction concept of granular media. The physicochemical factors of textile materials, such as shape, size, surface charge, the hydrophobicity of fibres, and media thickness and colloidal properties, determine the strength of colloidal-fibrous media physicochemical interactions [11]. Presented in this paper is a potential way to extend colloidal filtration theory to textile fibrous media in order to explain the mechanism of attachment of colloids (bacteria) on a textile media surface.

1.1 Filtration theory

Bacteria attachment in porous media as predicted by colloid filtration theory provides a model for determining the physical and chemical factors of particle retention in porous media. Physical controls over bacteria attachment in porous media depend on the geometry of the porous media, as well as bacteria. The number of potential contacts of particles with a surface can be estimated based on a physical mechanism. This, in turn, facilitates the determination of the attachment of particles in porous media, which depends on the chemical forces affecting adhesion and repulsion [12].

Particle removal in a packed bed in a constant state using an attachment mechanism can be described using one-dimensional filtration equation 1 [13].

$$\frac{dC}{dL} = -\frac{3}{2}\frac{(1-f)}{d_c}\eta C \qquad (1)$$

where C is particle concentration (in number of bacterial per unit volume), L is the thickness of the filter bed, $(1–f)$ is the solid fraction, η is the single collector contact efficiency and d_c is the collector diameter. Integration of the thickness of the packed bed yield is given in basic filtration equation 2.

$$F_p = \frac{C}{C_0} = \exp\left(\frac{3\,(1-f)}{2d_c}L\eta\right) \qquad (2)$$

Where F_p is fractional penetration and this is an indicator of the balance between cell adsorption and desorption.

Physical factors that account for particle collisions with porous media are incorporated into the single collector contact efficiency (η). The single collector contact efficiency of a single media particle or collector (η) is a ratio, i.e. the rate at which particles strike the collector to the rate at which particles flow towards the collector.

Numerous analytical solutions have been used to specify the single collector contact efficiency for filtration through granular media. Primarily transport mechanisms are used to develop the model for the theoretical calculation of single collector contact efficiency.

The Yao model, represented by equations 3–5 describing deep bed filtration for liquid filtration, were proposed by Logan et al. [14]. Single collector contact efficiencies for this model are based on spherical collectors.

$$\eta_D = 4Pe^{-2/3} \qquad (3)$$

$$\eta_I = \frac{3}{2}R^2 \qquad (4)$$

$$\eta_G = G \qquad (5)$$

Here, η_D, η_I and η_G represent theoretical values for the single collector contact efficiency when the sole transport mechanisms are diffusion, interception, or sedimentation, respectively. Single collector contact efficiency calculated numerically can be approximated by the sum of analytical equation 6. In other words:

$$\eta_0 = \eta_D + \eta_I + \eta_G \quad (6)$$

Single collector contact efficiencies are a dimensionless number and are developed from correlations using equations 7–9.

$$Pe = \frac{U_0 d_c}{D} \quad (7)$$

$$R = \frac{d_p}{d_c} \quad (8)$$

$$G = \frac{U_p}{U_0} \quad (9)$$

Where P_e is the peclet number, R and G are interception and gravitational numbers, U_0 and U_p are filter super facial velocity (L/T) and particle settling velocity (L/T), D is particle diffusivity (L^2/T), d_p is the particles diameter and d_c is the collector diameter. The particle settling velocity is obtained using equation 10.

$$U_p = \frac{g(p_p - p_f)d_p^2}{18\vartheta p_f} \quad (10)$$

μ and ϑ, dynamic and kinematic viscosity ($M\,L^{-1}\,T^{-1}$) of fluid g is the gravitational constant (L/T), where p_p and p_f the particle and fluid density (M/L^3). The particle diffusivity is obtained using the Stokes-Einstein equation (equation 11).

$$D = \frac{kT}{3\pi\mu d_p} \quad (11)$$

where k ($M\,L^2\,T^{-2}\,K^{-1}$) is Boltzmann's constant and T (K) is the absolute temperature.

The quantitative assessment of bacterial attachment to a collector surface is carried out by determining the collision efficiency (attachment) factor (α), and is often expressed as the ratio of experimental single collector efficiency (η), calculated using equation 2, to the predicted single collector efficiency (η_o), calculated using equation 6, or the possibility that a collision in an attachment, which is obtained using equation 12.

$$\alpha = \frac{\eta}{\eta_0} \quad (12)$$

2 Physicochemical factors of textile fibrous media affecting the removal of colloidal particles

2.1 Fibre size/diameter

In textile porous media, the attachment of colloids on the surface of a fibre is influenced by the fibre diameter. It has been reported that a lower fibre diameter will result in the higher removal efficiency of colloids due to the high specific surface area and good interconnectivity of pores [15]. The mean pore size of a fibrous media is highly dependent on the fibre diameter [16]. Eichhorn and Sampson used a theoretical model to demonstrate that the fibre diameter plays an important role in controlling the pore size of an electrospun nanofibrous network used for water filtration [17]. Zhou et al. [18] studied the removal of colloidal particles in cellulose acetate nanofibers membranes at different fibre diameters. They found that membranes with a lower fibre diameter had a higher removal efficiency than membranes with a higher fibre diameter. Desai et al. [19] studied the bacteria removal efficiency of nanofibers filter media by varying the diameter of the fibre. They reported that an increase in fibre diameter resulted in a decrease in filtration efficiency. It has been reported that the fibre diameter in textile filter media plays an important role in improving filtration efficiency.

2.2 Fibre shape/cross section

Many studies have been carried out on the effect of the shape of the fibre in textile media on colloidal removal in the filtration process. A higher projected surface area resulting from a different cross-section facilitates the probability of capturing colloids particles. Recently, hollow nanofiber membranes have emerged as substrates for use in liquid filtration [20]. Wang et al. [21] found that hollow fibre membranes have excellent intrinsic separation properties due to their highly porous and narrow pore size distribution, which leads to high filtration efficiency. Fibre cross-section could also be considered an important factor in colloidal filtration in textile filter media.

2.3 Fibre media thickness

The thickness of the media also affects the removal efficiency of a filter. Kaur et al. [22] suggested that if a fibrous media is used to separate sub-microns particles, a thicker fibrous layer is required to reduce the overall average pore size of the media. A higher media thickness is associated with increased colloidal removal due to the overlapping of the fibres in the media, resulting in fine sized pores, which facilitates the trapping of particles [18]. It has also been reported that the removal of clay particles increases with an increase in the thickness of the polypropylene fibrous barrier. It was claimed that a thicker barrier should provide more chances for the interception of clay particles [23–25].

2.4 Fibre hydrophobicity

The hydrophobicity of textile fibres is considered an important chemical factor that affects colloidal removal in textile fibrous media. Most colloidal particles are hydrophobic in nature. Hydrophobic interaction plays an important role in the efficient removal of colloidal particles [26]. The kinetics of the capture of colloidal particles is also determined by the magnitude of the hydrophobic interaction between particles and collectors. Hydrophobic interaction increases with an increase in the hydrophobicity of the filter media. The hydrophobicity of the media is characterised in terms of contact angle value [11]. Arnold et al. [27] reported that hydrophobicity is directly proportional to the contact angle of water with its surface and inversely proportional to the work of adhesion. Fletcher et al. [28] found a strong positive correlation between the number of bacteria attached to the surface and the

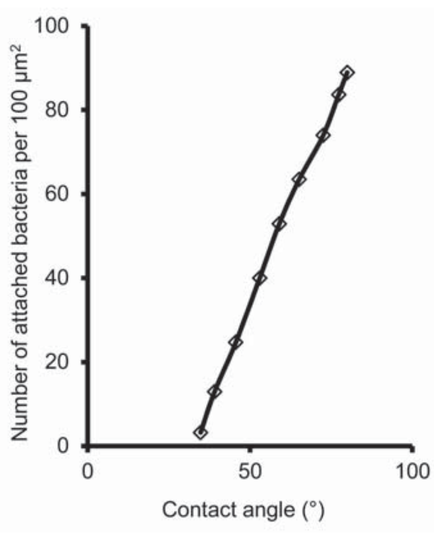

Figure 1: Relationship between bacteria attachment and the water contact angle on materials [28]

hydrophobic nature of polymers, as determined by the contact angle. It is evident in Figure 1 that an increase in the contact angle results in increased bacteria attachment. Pringle et al. [29] calculated a lower work of adhesion for nylon (98 mJ/m^2) than for glass (146 mJ/m^2). In an experiment with two pseudomonas species, it was observed that the attachment of these cells was higher to the nylon fibres than to the borosilicate glass surface because of the higher hydrophobicity of the nylon fibre.

2.5 Fibre surface charge

The removal of colloidal particles using relatively wide pore size fibrous media can be influenced not only by sieving parameters (pore size and pore size distribution) but also by the chemical interaction taking place between the colloidal particles and fibrous media [30, 31]. Cookson et al. [32] reported that attachment is brought about by the colloid-media chemical interaction controlled by the surface properties of the respective materials. Surface charge is one of the most important surface properties controlling the effective attachment of colloids on the fibre surface in textile fibrous media. It was reported that a possible mechanism for the removal of smaller-sized colloidal particles could be the electrostatic attraction between the opposite charges of the fibres and the particles, which causes the deposition of particles on the fibre surface [33–35]. The fibre surface charge is characterised in terms of zeta potential. It is measured using a streaming potential method on the surface of the fibres. The surface charges of fibres are the result of the disassociation of fibre surface groups in an aqueous medium. The isoelectric point (IEP) is the pH value corresponding to zero zeta potential and is different from fibre to fibre, depending on the surface properties [36]. Kang et al. [33] studied the adsorption of negatively charged nanoparticles on cationic, surfactant-treated microporous polypropylene filters. They reported that filtration efficiency can be increased from 10% to 90% through this surface modification. This can be attributed to the lowering energy barrier between the particles and filter media. Druet et al. [37] investigated the removal efficiency of heavy metal using positively charged, chitosan-treated polyethylene terephthalate geotextiles. They claimed that the higher positive charge of the media at an acidic pH will result in higher metal removal efficiency. In the desalination process based on textile nanofibers membranes, most membranes are characterised by a negative surface

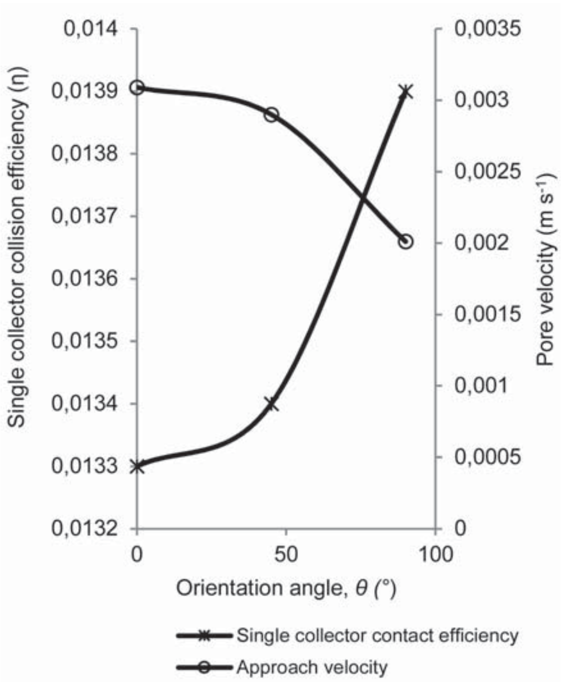

Figure 4: Effect of fibre orientation on single collector contact efficiency and approach velocity [42]

To quantitatively compare removal efficiency with different fibre orientations under identical solution conditions, the value of collision (attachment) efficiency (α) is calculated using equation no. 12, which is used in colloidal filtration theory. It has been reported that a high fibre orientation angle may lead to the exposure of a greater surface area for the striking

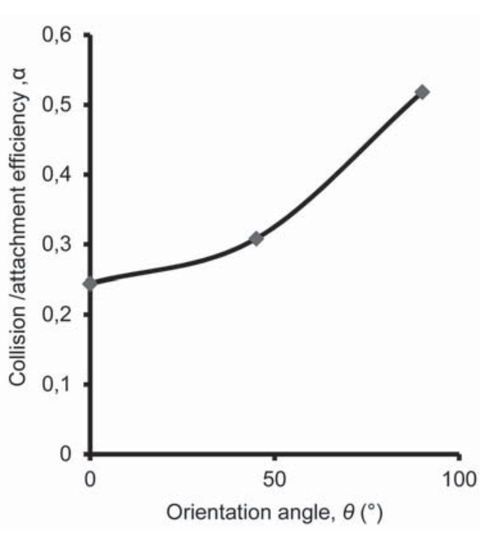

Figure 5: Collision efficiency as a function of the orientation angle [42]

of bacteria, resulting in high collision efficiency. A higher collision efficiency means higher bacteria attachment, where its maximum value is 1. It is evident from Figure 5 that an increase in fibre orientation results in an increase in collision efficiency.

3.2 Effect of fibre mass on bacteria removal efficiency

In another study conducted by Roy et al [43] on the effect of fibre mass on bacterial attachment, it was determined that removal efficiency increases with an increase in media mass up to a certain level (Figure 6). This is due to the change in single collector

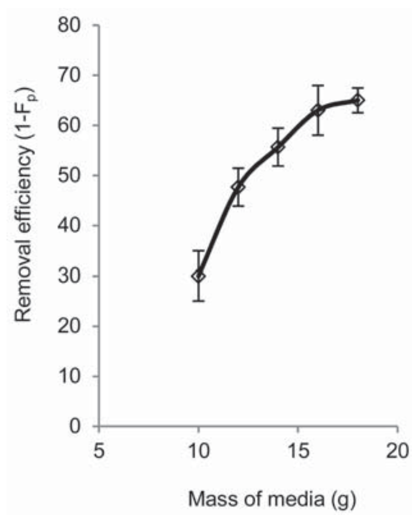

Figure 6: Removal efficiency as a function of media mass [43]

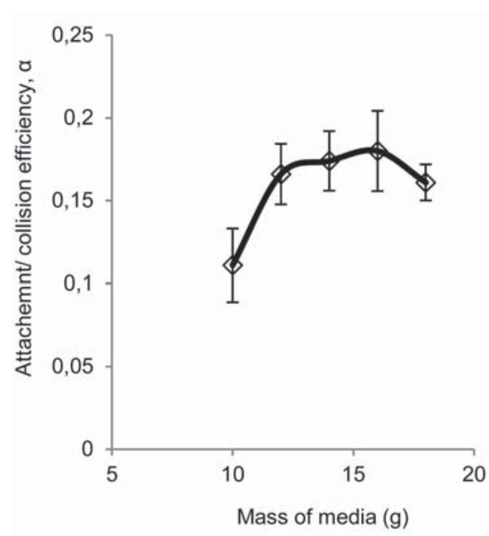

Figure 7: Collision efficiency as a function of media mass [43]

charge to enhance the removal of dissolved salts [38, 39]. Berg et al. [40] found that the electrostatic repulsion force of negatively charged pesticides on the surface of a negatively charged membrane is expected to enhance the overall removal efficiency.

Based on the above literature, it can be concluded that the physicochemical factors of textile fibrous media are identified on the basis of filtration efficiency, which is expressed in terms of the concentration variation of colloidal particles in input and output water. The effect of physicochemical factors on the mechanism of attachment of colloidal particles, primarily bacteria on textile fibrous media, may also be systematically investigated by using colloidal filtration theory.

3 Selected approaches to the application of colloidal filtration theory for textile material

An attempt has been made by a few researchers to use colloidal filtration theory to explain colloidal removal by an attachment mechanism in textile porous media. Dagaonkar et al. [41] used DLVO theory to explore the effect of solution chemistry on colloidal removal in nonwoven polyester filter fabric.

They reported that under unfavourable attachment conditions using bivalent salt ($CaCl_2$), removal efficiency increased from 35% to 62% compared to monovalent salt (NaCl), while the removal efficiency remain constant at around 38% for the ionic strength range of 0 to 100 mM (Figure 2).

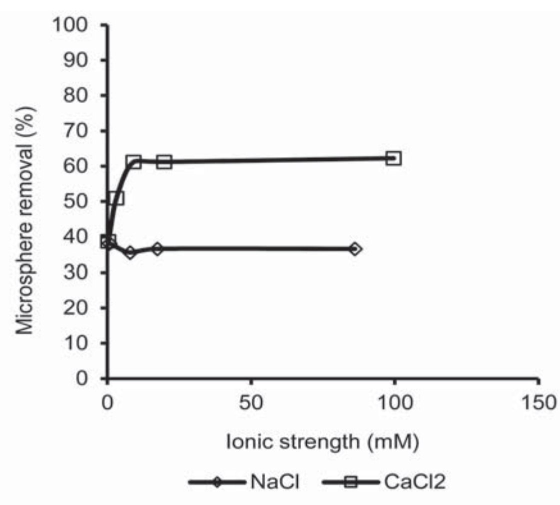

Figure 2: Microsphere removal as a function of ionic strength using different types of salts [41]

3.1 Effect of fibre orientation on bacteria filtration

Roy et al [42] investigated the attachment of bacteria to fibrous material as a function of fibre orientation to the direction of the liquid flow. Removal trends were explained on the basis of colloidal filtration theory. They reported that by changing fibre orientation from 0° to 90°, bacteria removal efficiency increased from 30% to 54.54%, suggesting that the attachment of bacteria on the media surface depends on fibre orientation (Figure 3)

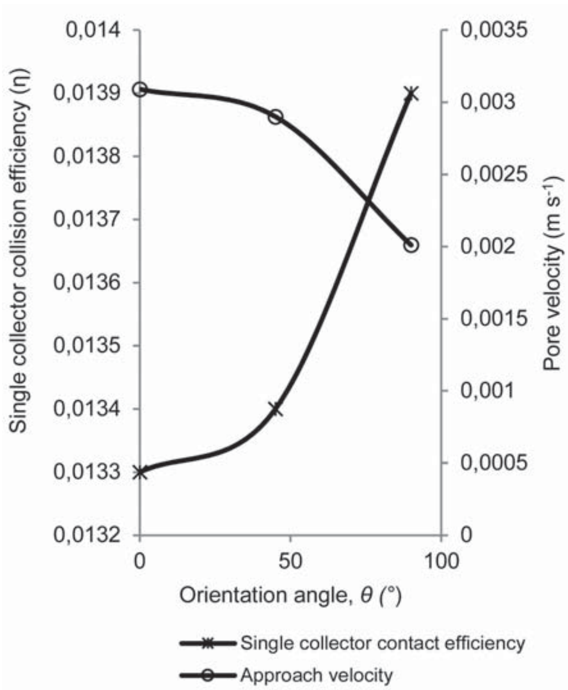

Figure 3: Removal efficiency as a function of the fibre orientation angle [42]

It is evident from Figure 4 that single collector efficiency increases from 1.33×10^{-2} to 1.39×10^{-2} by changing fibre orientation from 0° to 90˚. This is due to a decrement in the approach velocity of the filtration system from 3.09×10^{-3} to 2.01×10^{-3} m/s. Enhanced single collector contact efficiency by increasing fibre orientation has therefore been attributed to a change in the approach velocity of water in the filtration system. A potential explanation is that a high fibre orientation angle may lead to the exposure of a greater surface area for the striking of bacteria, resulting in high collector contact efficiency.

contact efficiency and attachment/collision efficiency, as observed from experimental data regarding removal efficiency.

It is evident from Figure 7 that changing the media mass increases and then decreases collision efficiency (α).

3.3 Effect of different fibrous material on bacterial attachment

Many researches have studied the effect of different media material on bacterial attachment in textile fibrous media. Roy et al. [44] reported that nylon

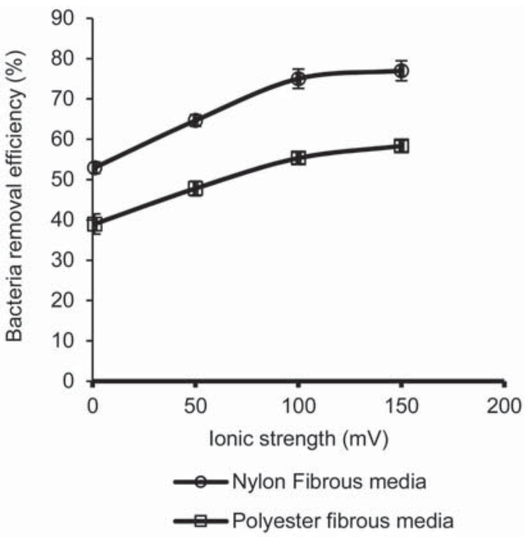

Figure 8: Effect of ionic strength on bacteria removal in different fibrous media [44]

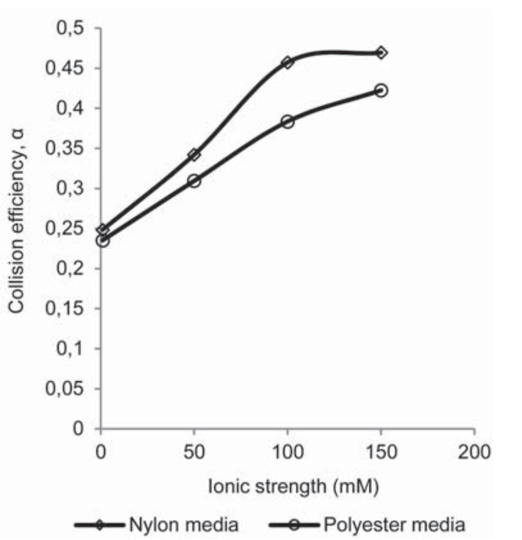

Figure 9: Collision efficiency as a function of ionic strength for different media material [44]

fibrous media demonstrates a higher removal efficiency than polyester fibrous media for the same solution chemistry (Figure 8). The bacteria removal efficiency of nylon and polyester fibrous filter media are explained based on colloidal filtration theory.

The removal and attachment of bacteria on a fibrous surface thus increases with an increase in ionic strength, which can be attributed to a change in collision efficiency. It is evident from Figure 9 that the change in collision efficiency is higher for nylon than for polyester, resulting in a higher removal efficiency by nylon fibrous media.

4 Conclusion

The reported study demonstrated that the fibre orientation of the filter media may play an important role in bacterial attachment. Bacteria attachment and removal efficiency increase with an increase in the fibre orientation angle. According to colloidal filtration theory, this is possible due to a change in the collision (attachment) efficiency of the fibrous media. Bacteria attachment and removal efficiency increase with an increase in media mass up to a certain level. It is also evident from reported studies that media materials play an important role in bacterial attachment in a fibrous packed bed.

The higher bacteria removal efficiency of nylon fibrous media than polyester fibrous media is due to the higher collision efficiency of nylon fibre (0.24 to 0.46) than polyester fibre (0.23 to 0.42) at the ionic strength range of 1mM to 150 mM.

Hence, the concept of dimensionless α (attachment efficiency) or η (single collector contact efficiency) of a granular media filter can be extended to textile filter media for the purpose of explaining the mechanism of attachment of colloids (bacteria) on textile fibrous media.

References

1. DENOVIO, Nicole M., SAIERS, James E., RYAN, Joseph N. Colloid movement in unsaturated porous media: recent advances and future directions. *Vadose Zone Journal*, 2004, **3**(2), 338–351, doi: 10.2113/3.2.338.

2. MCCARTHY, John E., ZACHARA, M. John. Subsurface transport of contaminants. *Environmental Science and Technology*, 1989, **23**, 469–502, doi: 10.1021/es00063a001.
3. GITIS, Vitaly, RUBINSTEIN, Isaak, LIVSHITS, Maya, ZISKIND, Gennady. Deep-bed filtration model with multistage deposition kinetics. *Chemical Engineering Journal*, 2010, **163**(1–2), doi: 10.1016/ cej.2010.07.044.
4. DAI, Xiaojun, HOZALSKI, Raymond M. Evaluation of microspheres as surrogates for cryptosporidium parvum oocysts in filtration experiments. *Environmental Science & Technology*, 2003, **37**(5), 1037–1042, doi: 10.1021/es025521w.
5. DAI, Xiaojun, HOZALSKI, Raymond. Effect of NOM and biofilm on the removal of *Cryptosporidium parvum* oocysts in rapid filters. *Water Research*, 2002, **36**, 3523–3532, doi: 10.1016/ S0043-1354(02)00045-3.
6. ELIMELECH, Menachem. Spatial distributions of *Cryptosporidium* oocysts in porous media: evidence for dual mode deposition. *Environmental Science & Technology*, 2005, **39**(10), 3620–3629, doi: 10.1021/es048289y.
7. BOLLER, Marcus, KAVANAUGH, M. C. Particle characteristics and headloss increases in granular media filtration. *Water Research*, 1995, **29**, 1139–1149, doi: 10.1016/0043-1354-(94)00256-7.
8. LEE, Jungjune, CHA, Jaehwan, AIM, Roger Ben, HAN, K. B., KIM, Chang-Gyun. Fiber filter as an alternative to the process of flocculation – sedimentation for water treatment. *Desalination*, 2008, **231**(1–3), 323–331, doi: 10.1016/j. desal. 2007.11.051.
9. LEE, Jungjune, JOHIR, Md Abu Hasan, CHINU, Khorshed, VIGNESWARAN, S., KANDASAMY, J., KIM, Chang-Gyun, SHAW, K. Novel pretreatment method for seawater reverse osmosis: Fibre media filtration. *Desalination*, 2010, **250**(2), 557–561, doi: 10.1016/j.desal.2009.09.023.
10. WANG, Chiu-Sen. Electrostatic forces in fibrous filters – a review. *Powder Technology*, 2001, **118**(1–2), 166–170, doi: 10.1016/S0032-5910(01)00307-2.
11. PLAKAS, Konstantinos V., KARABELAS, Anastasios J. Removal of pesticides from water by NF and RO membranes — A review. *Desalination*, 2012, **287**, 255–265, doi: 10.1016/j. desal.2011.08.003.
12. ADAMS, T. Bacterial attachment in porous media. The University of Arizona, 1992.
13. YAO, Kuan-Mu, MOHAMMAD, T. Habibian, O'MELIA, Charles R. Water and waste water filtration: concept and applications. *Environmental Science & Technology*, 1971, **5**(11), 1105–1112, doi: 10.1021/es60058a005.
14. LOGAN, Bruce E., JEWETT, D. G., ARNOLD, R. G., BOUWER, E. J., O'MELLIA, Charles R. Clarification of clean-bed filtration model. *Journal of environmental engineering*, 1995, **121**(12), 869–873, doi: 10.1061/(ASCE)0733-9372(1995) 121:12(869).
15. LI, Dapeng, FREY, Margaret, W., JOO, Yong L. Characterization of nanofibrous membranes with capillary flow porometry. *Journal of Membrane Science*, 2006, **286**, 104–114, doi: 10.1016/j.memsci.2006.09.020.
16. RJU, Young Jun, KIM, Hak Yong, LEE, Keun Hyung, PARK, Heui Chon, LEE, Douk Rae. Transport properties of electrospun nylon 6 nonwoven mats. *European Polymer Journal*, 2003, **39**, 1883–1889, doi: 10.1016/S0014-3057-(03)00096-X.
17. HSIEH, Y. C., YANO, H., NOGI, M., EICHHORN, S. J. An estimation of the Young' s modulus of bacterial cellulose filaments. *Cellulose*, 2008, **15**, 507–513, doi: 10.1007/s10570-008-9206-8.
18. ZHOU, Zhengping, LIN, Wei, WU, Xiang-Fa. Electrospinning ultrathin continuous cellulose acetate fibers for high-flux water filtration. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 2016, **494**, 21–29, doi: 10.1016/j. colsurfa.2015.11.074.
19. DESAI, Keyur, KIT, Kevin, LI, Jiajie, DAVIDSON, Michael, ZIVANOVIC, Svetlana, MEYER, Harry. Nanofibrous chitosan non-wovens for filtration applications. *Polymer*, 2009, **50**(15), 3661–3669, doi: 10.1016/j.polymer.2009. 05.058.
20. FENG, Chaoyang, KHULBE, Kailash, MATSUURA, T., TABE, Shahram, ISMAIL, Ahmad Fauzi. Preparation and characterization of electro-spun nanofiber membranes and their possible applications in water treatment. *Separation and Purification Technology*, 2013, **102**, 118–135, doi: 10.1016/j.seppur.2012.09.037.
21. WANG, Peng, TEOH, May May, CHUNG, Tai-Shung. Morphological architecture of dual-layer hollow fiber for membrane distillation with higher desalination performance. *Water Research*, 2011, **45**(17), 5489–5500, doi: 10.1016/j. watres.2011.08.012.
22. KAUR, Satinderpal, GOPAL, Renuga, NG, Wun Jern, RAMAKRISHNA, Seeram, MATSUURA, Takeshi. Next-Generation fibrous media for water treatment. *MRS Bulletin*, 2008, **33**(1), 21–26, doi: 10.1557/mrs2008.10.
23. YU, Jianghua, KIM, Youngchul. Performance evaluation and modeling of synthetic-fiber barrier in the treatment of turbid water. *Water Environment Research*, 2013, **85**(7), 596–603, doi: 10.2175/106143013X13698672321427.

24. LIU, Li, XU, Zhonghou, SONG, Cunyi, GU, Qingbao, SANG, Yimin, LU, Guilan, HU, Hualong, LI, Fasheng. Adsorption-filtration characteristics of melt-blown polypropylene fiber in purification of reclaimed water. *Desalination*, 2006, **201**(1–3), 198–206, doi: 10.1016/j. desal. 2006.02.014.
25. YU, Jianghua, YU, Haixia, KIM, Youngchul. Model development and application design of fiber mat used for turbid runoff treatment. *Environmental Science and Technology*, 2013, **34**(11), 1429–1437, doi: 10.1080/09593330.2012.752873.
26. EDWARD, S. K. Chian, BRUCE, Willis N., FANG, H. P. Herbert. Removal of pesticides by reverse osmosis. *Environmental Science & Technology*, 1975, **9**(6), 52–59, doi: 10.1021/es60099a009.
27. LOGAN, E. Bruce, HILBERT, A. Thomas, ARNOLD, G. Robert Removal of bacteria in laboratory filters: models and experiments. *Water Research*, 1993, **27**(6), 955–962, doi: 10.1016/0043-1354(93)90059-Q.
28. FLETCHER, Madilyn, LOEB, G. I. Influence of substratum characteristics on the attachment of a marine pseudomonad to solid surfaces. *Applied and environmental microbiology*, 1979, **37**(1), 67–72.
29. PRINGLE, James H., FLETCHER, Madilyn. Influence of substratum wettability on attachment of fresh- water bacteria to solid-surfaces. *Applied and Environmental Microbiology*, 1983, **45**(3), 811–817.
30. BOUSSAHEL, Rachdi, BOULAND, S., MOUSSAOUI, K. M., MONTIEL, A. Removal of pesticide residues in water using the nanofiltration process. *Desalination*, 2000, **132**(1–3), 205–209, doi: 10.1016/S0011-9164(00)00151-X.
31. BOUSSAHEL, Rachdi, MONTIEL, A., BAUDU, Michel. Effects of organic and inorganic matter on pesticide rejection by nanofiltration. *Desalination*, 2002, **145**(1), 109–114, doi: 10.1016/S0011-9164(02)00394-6.
32. COOKSON, John T. Jr. Removal of submicron particles in packed beds. *Environmental Science & Technology,* 1970, **4**(2), 128–134, doi: 10.1021/es60037a005.
33. KANG, Peter K., SHAH, Dinesh O. Filtration of nanoparticles with dimethyldioctadecylammonium bromide treated microporous polypropylene filters. *Langmuir*, 1997, **13**(6), 1820–1826, doi: 10.1021/la961010+.
34. YANG, Shinhao, LEE, Grace W. M., LUO, Chin-Siang, WU, Chih-Cheng, YU, Kuo-Pin. Loading characteristics of filter pretreated with anionic surfactant for monodisperse solid particles. *Powder Technology,* 2005, **156**(1), 52–60, doi: 10.1016/j.powtec.2005.06.005.
35. HINESTROZA, Juan P., KIM, Joyoun, JASPER, Warren J. Charge characterization of an electrically charged fiber via electrostatic force microscopy. *Journal of Engineered Fibers and Fabrics*, 2006, **1**(2), 30–46, doi: 10.1177/155892500600100020.
36. DELGADO, Angel V., GONZÁLEZ-CABALLERO, Fernando, HUNTER, R. J., KOOPAL, Luuk K., LYKLEMA, J. Measurement and interpretation of electrokinetic phenomena. *Pure and Applied Chemistry*, 2005, **77**(10), 1753–1805, doi: 10.1351/pac200577101753.
37. DRUET, Julie, EL ACHARI, Ahmida, ISAAD, Jalal. Efficient removal of heavy metals from aqueous solution by chitosan-coated geotextiles based on polyethylene terephthalate. *Research on Chemical Intermediates*, 2015, **41**(11), 8855–8876, doi: 10.1007/s11164-015-1933-5.
38. XU, Yazhen, LEBRUN, Remi E. Investigation of the solute separation by charged nanofiltration membrane : effect of pH, ionic strength and solute type. *Journal of Membrane Science*, 1999, **158**(1−2), 93–104, doi: 10.1016/S0376-7388-(99)00005-8.
39. DESHMUKH, Shivaji, CHILDRESS, Amy E. Zeta potential of commercial RO membranes : influence of source water type and chemistry. *Desalination*, 2001, **140**(1), 87−95, doi: 10.1016/S0011-9164(01)00357-5.
40. BERG, P., HAGMEYER, Georg, GIMBEL, R. Removal of pesticides and other micropollutants by nanofiltration. *Desalination*, 1997, **113**(2−3), 205–208, doi: 10.1016/S0011-9164-(97)00130-6.
41. DAGAONKAR, Manoj, MAJUMDAR, Udayan. Effect of fluid flow, solution chemistry and surface morphology of fibrous material on colloid filtration. *Journal of Engineered Fibers and Fabrics*, 2012, **7**(3), 62–74, doi: 10.1177/155892501200700309.
42. ROY, Sukumar, GHOSH, Subrata, BHOWMICK, Niranjan. Application of colloidal filtration theory on textile fibrous media: effect of fiber orientation on bacterial removal efficiency and attachment. *Journal of The Institution of Engineers (India): Series E*, 2018, **99**(1), doi: 10.1007/s40034-018-0120-9.
43. ROY, Sukumar, GHOSH, Subrata, BHOWMICK, Niranjan. Application of colloidal filtration theory to bacterial attachment in textile fibrous media. *Tekstilec*, 2018, **61**(3), 171–178, doi: 10.14502/Tekstilec2018.61.171-178.
44. ROY, Sukumar, GHOSH, Subrata, BHOWMICK, Niranjan. Mechanism of bacterial attachment on textile fibrous media. *The Journal of The Textile Institute*, 2018, doi: 10.1080/00405000.2018.1533442.

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Impact of Finisher Drawframe Storage Variables on Combed Yarn Quality

Vpliv dejavnikov shranjevanja raztezanega pramena na kakovost česane preje

Original Scientific Article/*Izvirni znanstveni članek*
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Abstract
The cotton ring spinning preparatory is confronting the serious issue of combed sliver handling during sliver storage and processing. Combed sliver is more liable to stretching and failure due to low interfibre cohesion during the processing on a drawframe and speedframe. The combed sliver quality deteriorates if stored in older storage cans of decreased spring stiffness due to prolonged fatigue loading. The bottom position combed sliver processed from older cans results in sliver stretching and sometimes failures at speedframe creel due to high inter-sliver coils adhesion with adjacent sliver coils. The study deals with investigating the influence of the sliver coils position, storage can-spring stiffness and finisher drawframe delivery speed on combed cotton yarn unevenness, imperfections, breaking tenacity, breaking elongation and S3 hairiness. The experimental work and statistical analysis suggest that the sliver coils position and can-spring stiffness play a vital role in deciding combed yarn quality characteristics.
Keywords: combed sliver, can-spring stiffness, coils position, storage time

Izvleček
Pri pripravi na predenje prstanske bombažne preje se soočamo s pomembnimi problemi, povezanimi z ravnanjem s česanim pramenom med skladiščenjem in predenjem. Zaradi slabe kohezije med vlakni v česanem pramenu hitro pride do neželenih nekontroliranih raztegov, predpreja in preja postaneta bolj neenakomerni. Kakovost česanega pramena se poslabša, če ga skladiščimo v starejših loncih z zmanjšano togostjo vzmeti, ki je posledica preutrujenosti materiala. Predelava spodnjih plasti česanega pramena iz starejših loncev lahko vodi do neželenih raztegov in občasno pretrgov pramena na krilniku zaradi povečanega medsebojnega sprijemanja sosednjih ovojev. Študija se ukvarja s proučevanjem vpliva položaja ovojev, togostjo vzmeti v loncu in odvajalno hitrostjo raztezalnika na neenakomernost česane bombažne preje, količino napak, pretržno trdnost, pretržni raztezek in kosmatost preje. Eksperimentalno delo in statistična analiza sta pokazala, da položaj ovojev pramena in togosti vzmeti loncev močno vpliva na končno kakovost bombažne česane preje.
Ključne besede: česani pramen, togost vzmeti v loncu, položaj ovojev, čas shranjevanja

1 Introduction

At the finisher drawframe section in a combed ring spinning preparatory, hundreds of storage cans are used for sliver storage. The main component of a sliver storage container, which is also termed as the heart of the storage can, is its spring. The spring stiffness of these storage cans decreases with

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time due to fatigue loading and surface crack formation [1–2]. These older storage cans of reduced spring stiffness are extensively used in the spinning preparatory in India. In the last few years, there has been a growing interest in combed sliver handling during sliver deposition and withdrawal from storage cans. Moreover, combed sliver handling is an unavoidable quality issue while using older storage cans of reduced spring stiffness for combed sliver storage. Older can-springs deform more against the applied sliver load as compared to new springs due to the can-spring stiffness variation. The optimum spring pressure should be maintained for smoother operations and for fault-free sliver handling [3]. Furthermore, older can-springs can deteriorate stored combed sliver quality caused by sliver stretching during sliver deposition and withdrawal at a drawframe and speedframe, respectively. Previous studies showed that the storage can-spring condition should be monitored regularly after some prescribed time for fault-free roving and yarn [4–7].

The finisher drawframe machine holds a crucial position in quality improvement through fibre alignment in sliver and by producing a uniform sliver free from thick and thin places [8–10]. The improved fibre alignment in combed sliver is responsible for low interfibre cohesion, making combed sliver liable to stretching at the time of sliver deposition on a drawframe and during sliver withdrawal on a speedframe [11]. Previous research has documented that the fibre configuration in combed sliver is primarily affected by the drawframe speed [12]. The weight of the sliver is the major source of sliver stress during sliver deposition and can achieve about one-third of the combed sliver strength in a modern high-speed drawframe [13–14]. The imperfection free combed yarn can be produced at a ringframe by feeding consistent quality sliver at a finisher drawframe machine. For that, we need a correct sliver handling system [15–17]. However, to the authors' best knowledge, very few studies are available in the literature that discuss the issue of poor combed sliver handling due to improper can-spring stiffness. Previous studies also lack detailed explanations of the cause of variation in combed sliver quality at different sliver coils position in a storage can. Furthermore, the effect of allowing combed sliver storage time on the resultant yarn quality has not yet been studied. Combed sliver storage time is considered as a quality-reducing factor among the spinners and is a result of poor preparatory planning, maintenance loss and power loss.

Hence, a comprehensive study is required to examine the effect of a few imperative sliver storage variables at a finisher drawframe on combed yarn quality characteristics. The present research work is focused on studying the effect of few scarcely investigated finisher drawframe variables, such as sliver coils position, can-spring stiffness and delivery speed, on combed yarn unevenness, imperfections, tenacity, elongation and S3 hairiness.

2 Materials and methods

2.1 Material

Combed cotton extra-long variety from the south Indian states MCU-5 100% was used to produce sliver samples on a twin delivery finisher drawframe machine. The fibre properties were measured using a high volume instrument HVI900-spinlab. The cotton fibre specifications with 2.5% span length were 30.9 mm, fibre strength 24.61cN/tex and fibre fineness in micronaire was 4.2, used for the combed sliver sample preparation. The finisher drawframe sliver liner density 5.319 ktex was processed on a speedframe at the twist multiplier 1.34 to produce 0.641 ktex roving. Furthermore, the roving samples were fed to the ringframe machine to manufacture 14.22 tex yarn at the twist multiplier 4.2.

2.2 Methods

In order to investigate the effect of sliver coils position, can-spring stiffness and finisher drawframe delivery rate on combed yarn quality parameters, the three-factor and three-level Box-Behnken design was used to prepare the combed yarn samples to determine yarn unevenness, imperfections/km, breaking tenacity, breaking elongation and S3 hairiness index. The detail of levels is given in Table 1. A suitable randomization and replication technique was adopted at the time of sample preparation for an effective statistical analysis and to reduce the chances of error occurrence.

2.2.1 Experimental plan and yarn sample preparation

In order to optimise the number of runs, the Box-Behnken design was adopted for sample planning with coded and real values, as shown in Tables 1

Table 1: Box-Behnkenexperimental design

Standard runs	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Sliver coils position	–1	1	–1	1	–1	1	–1	1	0	0	0	0	0	0	0
Spring stiffness [N/m]	–1	–1	1	1	0	0	0	0	–1	1	–1	1	0	0	0
Delivery speed [m/min]	0	0	0	0	–1	–1	1	1	–1	–1	1	1	0	0	0

Table 2: Factors and corresponding levels of variation

Variables	–1	0	+1
Sliver coils position	Low	Middle	Top
Spring stiffness [N/m]	170	190	210
Delivery speed [m/min]	250	400	550

and 2. Initially, older storage can-spring stiffness was measured using predetermined dead weights and then categorized into three different groups of spring stiffness after prolonged scrutiny, as indicated in Table 2. Spring stiffness was measured in N/m. It is observed that the deformation is higher against the applied load in the case of older cans compared to the new cans. The main cause for higher deformation in older cans against applied sliver load was a decrease in spring stiffness due to fatigue loading over the years.

Combed drawn sliver samples were deposited in storage cans of different spring stiffness at 250 m/min, 400 m/min and 550 m/min delivery rates at the finisher drawframe machine. In order to assess the quality of stored combed sliver at different coil positions, the top, middle and bottom sliver coils position were considered. Each sliver coils position contained an equal length of combed sliver as the total length of deposited combed sliver was divided into three equal parts, representing each sliver coils position. In order to access the effect of sliver storage time, two cases were considered after consulting with industry experts, i.e. with 8 hours of sliver storage time after a full can being ejected from the finisher drawframe and without allowing any sliver storage time or 0 hour storage time.

2.2.2 Yarn testing

The yarn sample was conditioned under standard atmospheric conditions, in a tropical atmosphere of 27 °C± 2 °C temperature and 65 ± 2% relative humidity, while the number of readings was determined according to the variation in a sample in order to achieve a 95% confidence interval. Appropriate numbers of combed yarn samples were tested by calculating and considering the coefficient of variation in all cases. Yarn unevenness and imperfections/km were measured on an Uster® Tester 4-S according to ASTM D 1425-96. The total combed yarn imperfection/km was calculated by adding –50% thin, +50% thick and +200% neps. The Zweigle hairiness index (S3) was measured using a Zweigle G565 instrument, considering the hairiness parameter "S3" (number of hairs equal or greater than 3 mm) as per ASTM D 5647-01. Yarn breaking tenacity and breaking elongation were measured on a Premier TensoMaxx at 500 mm gauge length and according to ASTM D 2256-02.

3 Results and discussion

The detail of all observed response yarn test results is shown in Table 3.

Statistical analysis

The influence of independent control variables was statistically investigated using ANOVA at 95% confidence level using statistical software. The p-value helped determining the significance of the results. A low *p*-value (≤ 0.05) indicates a strong effect of the control factor on the observed response, whereas a high *p*-value (> 0.05) indicates a weak effect. The independent control factors, i.e. sliver coils position, spring stiffness and finisher drawframe delivery speed, were considered to check any statistical significance. The analysis of variance summary is as shown in Tables 4a and 4b.

Table 3: Control factors and corresponding observed responses

Runs	Variables			Responses without allowing any storage time					Responses at 8 hours of storage time				
	Sliver coils position	Spring stiffness [N/m]	Delivery speed [m/min]	U [%]	Imperfection [1/km]	Breaking tenacity [cN/tex]	Breaking elongation [%]	Hairiness, S3	U [%]	Imperfections [1/km]	Breaking tenacity [cN/tex]	Breaking elongation [%]	Hairiness, S3
1	–1	–1	0	11.41	135	15.89	3.75	1770	11.73	152	15.36	3.56	1864
2	1	–1	0	10.75	105	16.89	4.11	1149	11.38	141	16.30	3.88	1461
3	–1	1	0	10.69	111	17.05	4.37	1422	10.94	139	16.64	4.16	1678
4	1	1	0	10.59	93	18.68	4.41	711	10.77	112	17.09	4.47	957
5	–1	0	–1	11.34	131	16.29	3.68	1580	11.58	126	16.51	3.73	1640
6	1	0	–1	10.66	104	17.52	4.53	1050	10.61	104	17.67	4.44	1015
7	–1	0	1	11.31	92	16.73	4.08	1495	11.41	133	16.73	3.97	1523
8	1	0	1	10.57	98	18.23	4.41	780	11.19	101	16.78	4.32	1035
9	0	–1	–1	11.21	114	16.22	3.98	1561	11.28	130	16.28	3.95	1131
10	0	1	–1	10.59	102	16.97	4.62	887	11.32	89	17.39	4.41	1011
11	0	–1	1	11.11	96	16.65	4.43	1295	11.23	119	16.50	4.36	1107
12	0	1	1	10.57	94	18.77	4.92	891	10.57	99	17.52	4.86	927
13	0	0	0	10.57	97	17.93	4.71	845	10.62	97	17.04	4.52	895
14	0	0	0	10.61	91	18.06	5.05	861	10.59	110	16.93	4.89	861
15	0	0	0	10.58	89	17.96	4.81	877	10.65	116	16.87	4.78	1004

Table 4a: ANOVA general linear model summary through p-value analysis: Effects without any sliver storage time

Spinning variables	U [%]	Imperfections [1/km]	Breaking tenacity [cN/tex]	Breaking elongation [%]	Hairiness, S3
Sliver coils position	0.00[a)], s [b)]	0.01, s	0.00, s	0.00, s	0.00, s
Spring stiffness [N/m]	0.00, s	0.08, ns	0.00, s	0.00, s	0.00, s
Delivery speed [m/min]	0.05, ns [c)]	0.04, s	0.00, s	0.07, ns	0.00, s

Table 4b: ANOVA general linear model summary through p-value analysis: Effects after 8 hours of sliver storage

Spinning variables	U [%]	Imperfections [1/km]	Breaking tenacity [cN/tex]	Breaking elongation [%]	Hairiness, S3
Sliver coils position	0.03, s	0.00, s	0.00, s	0.00, s	0.00, s
Spring stiffness [N/m]	0.04, s	0.00, s	0.00, s	0.00, s	0.00, s
Delivery speed [m/min]	0.27, ns	0.12, ns	0.16, ns	0.08, ns	0.58, ns

[a)] p-value
[b)] s-significant if $p < 0.05$ at 95% confidence interval
[c)] ns-not significant if $p > 0.05$

3.1 Effect of control factors on combed yarn unevenness

It was observed that the combed yarn samples produced from sliver stored in older storage cans of can-spring stiffness 170 N/m and the yarn samples produced from the bottom position sliver coils result in higher unevenness as compared to the samples produced from the middle and top position sliver coils using 190 N/m and 210 N/m stiffness storage can-springs, as shown in the contour plots in Figure 1.The samples prepared without allowing any sliver storage time produced from the bottom sliver coils position using 170 N/m can-spring stiffness showed by 11.41% higher observed mean unevenness, which further increased after 8 hours of sliver storage time to 11.73%, as shown in the contour plots in Figure 1. At a lower delivery speed, relatively higher unevenness was observed in both cases as is indicated in Figure 1.

The main reason for stored sliver quality deterioration were poor sliver handling in older storage cans, older can-spring buckling, sliver contact with the rough

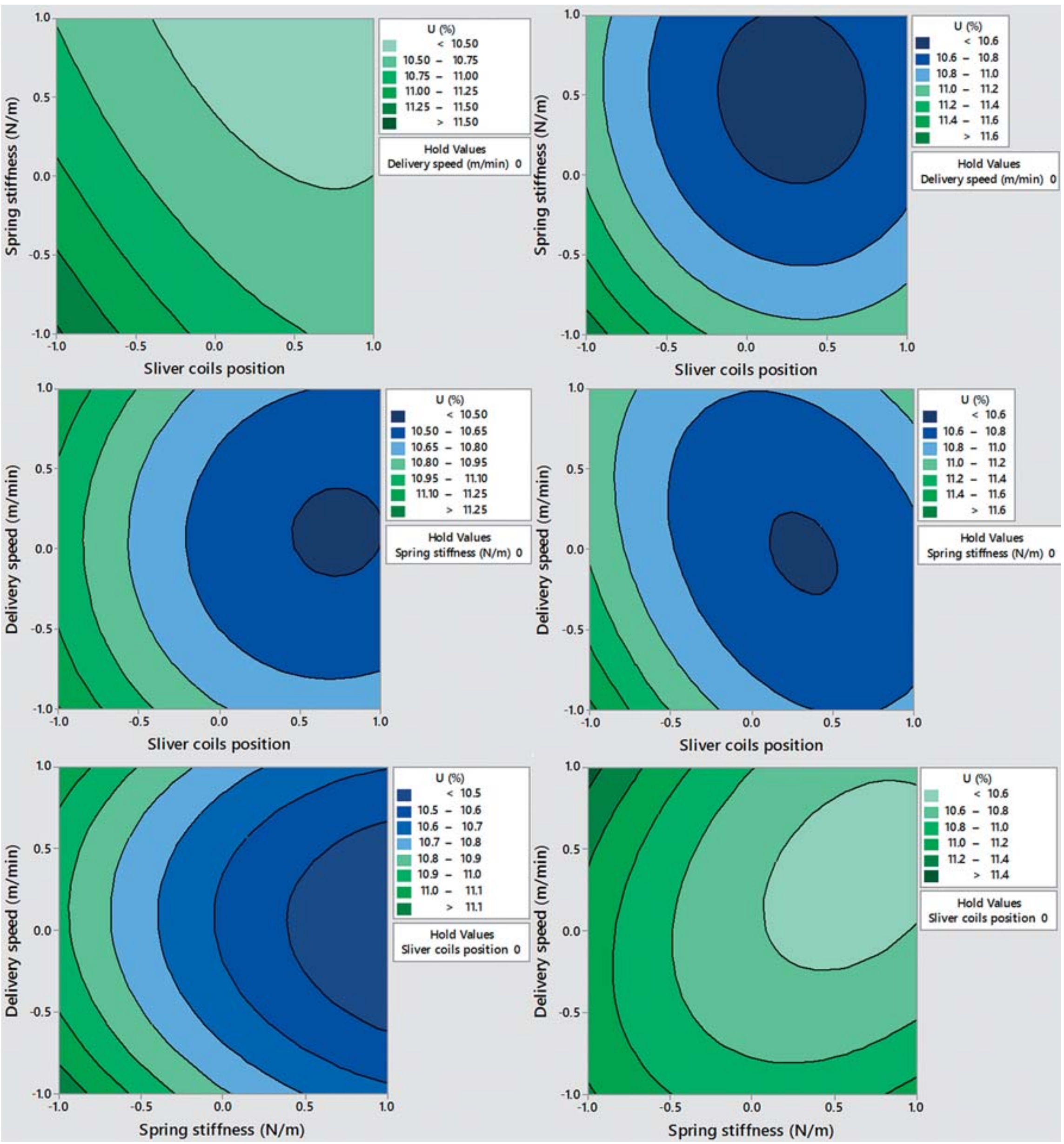

Figure 1: Effect of control factors on yarn unevenness at 0 hr (left) and 8 hrs (right) storage time

side wall of the container and frequent sliver failure at the speedframe creel due to the presence of higher inter-sliver coils adhesion at the bottom sliver coils position as shown in Figures 2–4. Due to the variation in force experienced by different sliver coils, the bottom sliver coils became flattened and experienced more adhesion with adjacent sliver coils at the time of sliver withdrawal at the speedframe, as shown in Figure 2. Consequently, higher sliver stretching and even sliver failure was observed at the speedframe creel and more frequent start-up breakage at the ringframe. The combined action of poor combed sliver handling in older storage cans and yarn samples produced from the bottom position sliver coils resulted in higher unevenness in the resultant yarn. The combed sliver stored in older storage cans of decreased can-spring stiffness experienced sliver rubbing against the container's rough wall due to can-spring buckling, as shown in Figure 4, and resulted in a relatively weaker, hairy and uneven roving, and yarn which also contributed to higher combed yarn unevenness. Furthermore, the combed yarn unevenness percentage was found higher at the samples produced from the bottom position sliver coils allowing 8 hours of sliver storage time, which is due to improved sliver coils adhesion with adjacent coils at the speedframe creel. However, relatively lower inter-sliver coils adhesion

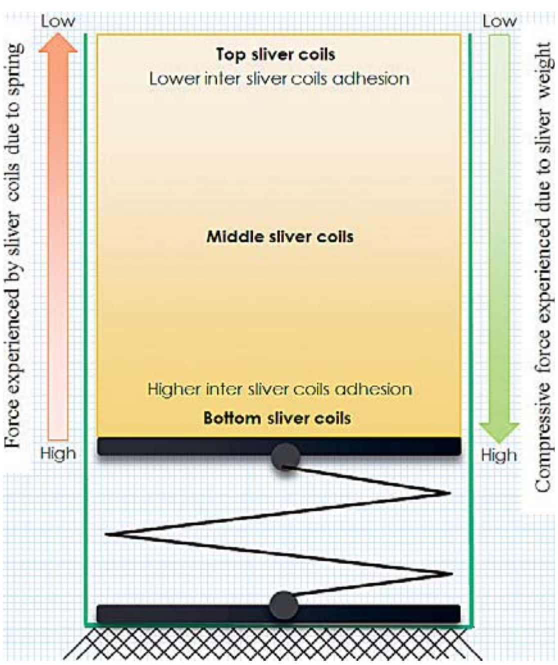

Figure 2: Forces experienced by different sliver coils position

was observed at the bottom position sliver coils samples produced without allowing any storage time.

Figure 3: Flattened bottom sliver coils at speedframe creel

Figure 4: Can-spring buckling on sliver storage in older can

Based on the statistical analysis conducted with a general linear ANOVA model and experimental results, it was found that the effect of the sliver coils position and can-spring stiffness is significant for yarn unevenness at 8 hours of storage time as well as without allowing any storage time; however, the effect of the delivery speed is marginal in both cases, as shown in the contour plots in Figure 1 and as vindicated in Table 4. Overall, the combed yarn unevenness was found higher at 8 hours storage of time as compared to the samples produced without allowing any storage time.

3.2 Effect of control factors on combed yarn imperfections

The uneven sliver results in faulty roving and yarn. The statistical analysis and experimental results reveal that the yarn produced from the bottom position sliver coils using older storage cans of spring stiffness 170 N/m showed a higher imperfection level with 135 imperfections/km at the yarn samples produced without allowing any storage time. A further increase in the imperfection level was observed at 8 hours of storage time with the highest mean value of 152 imperfections/km observed at the lowest spring stiffness and at the samples produced from the bottom position sliver coils, as shown in the contour plots in Figure 5.

The reason for a higher imperfection level in the resultant yarn was improved stickiness in the bottom sliver coils, and hairy and weak combed sliver, which results in more sliver stretching and sliver failure at the time of sliver withdrawal from older storage cans. As discussed earlier, older can-spring buckling resulted in combed sliver contact with the rough side wall of the storage container and deteriorated stored sliver quality by producing weaker and hairy sliver. The yarn samples produced from the bottom position sliver coils showed a higher imperfection level as these sliver coils experienced the highest compressive force, resulting in more contact with adjacent sliver coils and improved adhesion. Consequently, sliver splitting, stretching, the formation of thick & thin places, and even failure was observed at the time of sliver processing at the speedframe. Finally, the combed yarn samples produced from such hairy and weaker roving samples showed more imperfections in the resultant yarn.

In the case of samples produced without allowing any storage time, it was observed that total

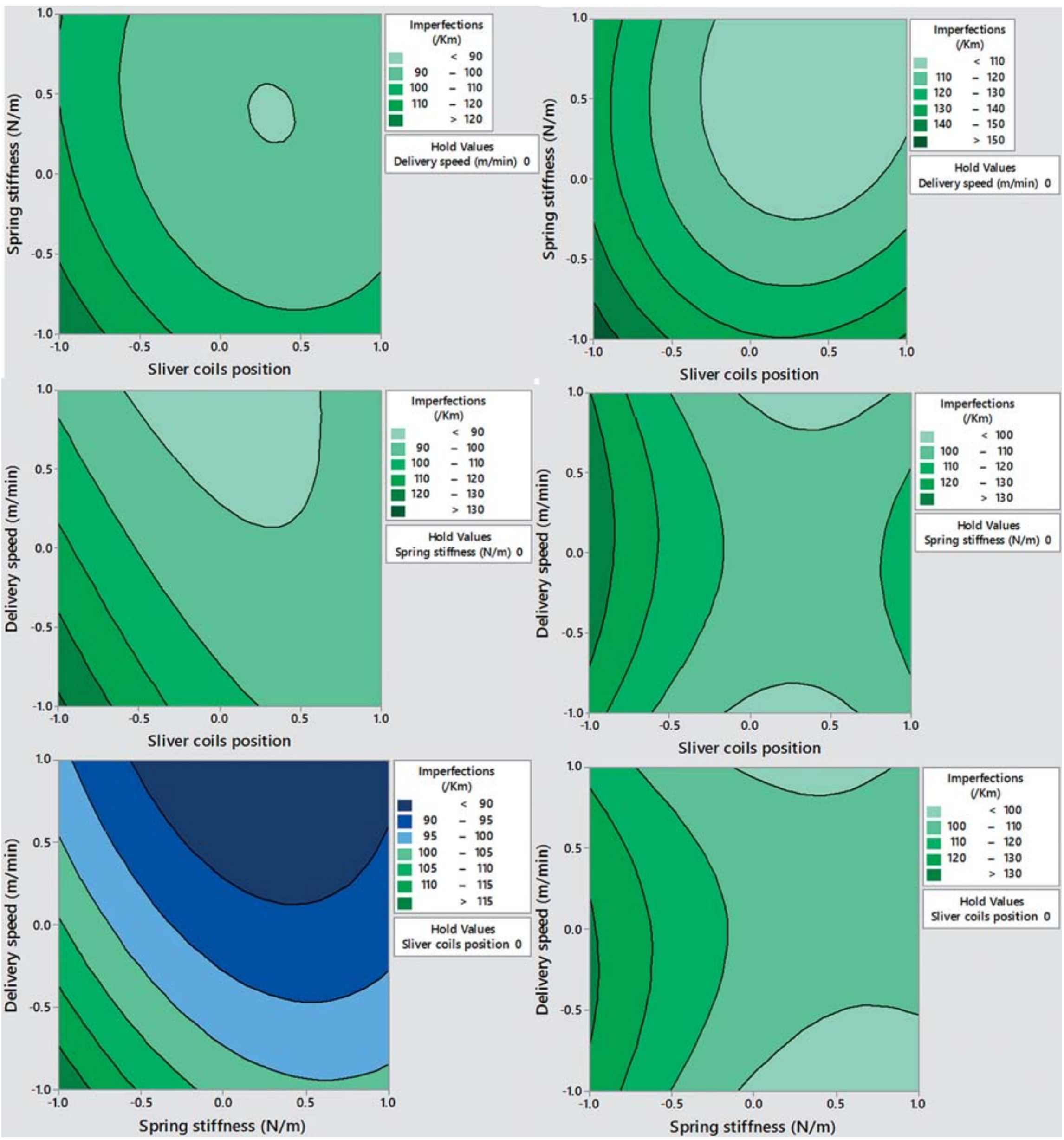

Figure 5: Effect of control factors on yarn imperfections at 0 hr (left) and 8 hrs (right) storage time

imperfections are lower at a higher finisher drawframe delivery speed, i.e. 550 m/min, and higher at a lower delivery speed, i.e. 250 m/min, which is a consequence of ineffective straightening of hooked fibres in the drafting zone at a higher delivery speed. A general linear ANOVA analysis suggested that the effect of the sliver coil position and delivery rate is significant for imperfection, whereas the observed effect is insignificant for can-spring stiffness at the samples produced without allowing any sliver storage time. Moreover, the effect of the sliver coils position and can-spring stiffness was found significant, whereas the effect of the delivery rate is insignificant for the samples produced by allowing 8 hours of sliver storage time.

3.3 Effect of control factors on combed yarn breaking tenacity

It was found that the resultant combed yarn breaking tenacity was higher at the samples produced

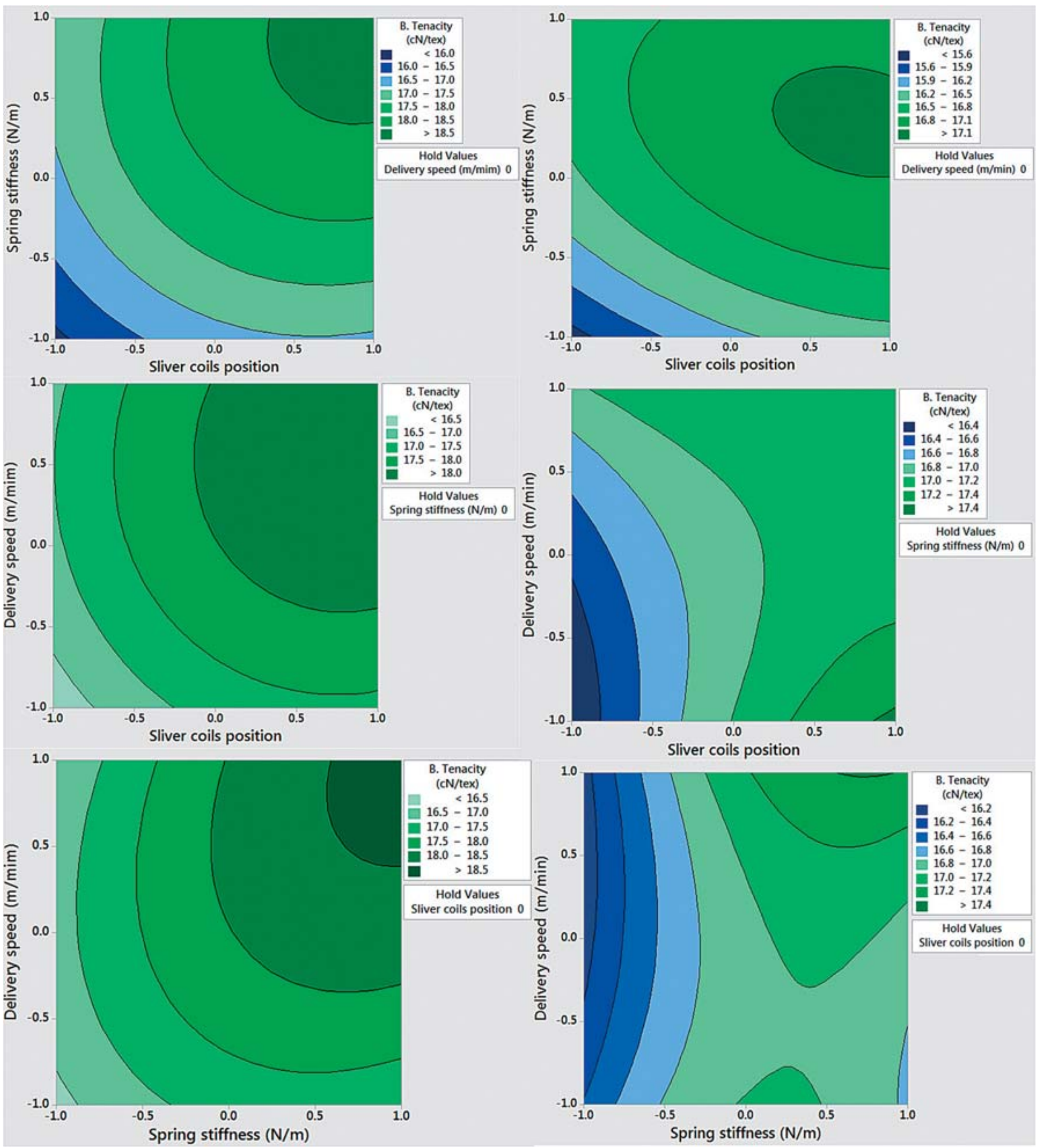

Figure 6: Effect of control factors on yarn breaking tenacity at 0 hr (left) and 8 hrs (right) storage time

from the storage cans of spring stiffness 210 N/m and the top position sliver coils compared to the samples produced from older storage cans. The contour plots in Figure 6 confirm the same, as at the samples produced without allowing any storage time, the upper range of breaking tenacity mean values was between 17 cN/tex and18.5 cN/tex, and at the samples produced by allowing 8 hours of sliver storage time, relatively lower breaking tenacity was observed with the upper mean values being between 16.6 cN/tex and17.4 cN/tex. Yarn breaking tenacity was found higher at a higher finisher drawframe delivery speed, i.e. 550 m/min, which is a consequence of less effective straightening of hooked fibres in the drafting zone, and higher centrifugal force inside the coiler at a higher delivery speed. Thus, the sliver, roving and yarn failure rate decreased and resulted in stronger and fault-free yarn with higher breaking tenacity. The weaker, hairy, flattened and stretched bottom position sliver coils from older storage cans resulted in weaker and irregular roving, and yarn of low breaking tenacity. Furthermore, it was observed that yarn breaking tenacity was relatively lower at the yarn samples produced at the 8 hours combed sliver storage time, which is a consequence of an additional improvement in the bottom sliver coils adhesion with adjacent coils, resulting in more sliver stretching and failure at the time of sliver withdrawal at the speedframe creel. This caused uneven resultant yarn with more imperfections (thick and thin places), resulting in a decrease in breaking tenacity of yarn samples produced from such roving samples.

The statistical analysis with ANOVA summary reveals that the effect of all control factors was found significant on combed yarn breaking tenacity in both cases of sliver storage time, except for the effect of the delivery rate, which was found insignificant for the samples produced by allowing 8 hours of sliver storage time.

3.4 Effect of control factors on combed yarn breaking elongation

The experimental results reveal that combed yarn samples produced from older storage cans of can-spring stiffness 170 N/m, bottom position sliver coils and at the finisher drawframe speed of 250 m/min showed lower breaking elongation, which is 3.68% with the lowest observed mean value in the case of samples produced without allowing any storage time compared to other yarn samples, as shown in Figure 7. Furthermore, it was found that the samples produced by allowing 8 hours of storage time showed a marginal decrease in breaking elongation with the lowest observed mean value of 3.56%, as shown in Figure 7. The causes of low breaking elongation are similar to that of low breaking tenacity due to the presence of higher unevenness and higher imperfections present in the yarn samples produced from older cans bottom sliver coils position at the 250 m/min drawframe delivery speed. Weaker, hairy and flattened sliver from the bottom sliver position resulted in weaker roving and resultant yarn with low breaking elongation. The analysis of variance showed that the effect of sliver coils position and can-spring stiffness is significant for combed yarn breaking elongation, whereas the effect of the delivery rate on breaking elongation is insignificant.

3.5 Effect of control factors on combed yarn hairiness

Lower S3 hairiness was observed at the samples produced at the 550 m/min finisher drawframe delivery rate using storage cans of spring stiffness 210 N/m and from the middle and top sliver coils positions. For the samples produced without allowing any storage time, the highest S3 hairiness with the S3 mean value 1770 was observed at 170 N/m can-spring stiffness and the bottom sliver coils position. In addition, the samples produced by allowing 8 hours of storage time encountered a further improvement in S3 hairiness at 170N/m spring stiffness, as well as the samples produced from the bottom sliver coils position with the S3 mean values 1864, as shown in the contour plots in Figure 8. Higher S3 hairiness observed in the case of samples produced from the bottom position sliver coils resulted from various reasons, including sliver rubbing with the rough side wall, can-spring buckling, sticky & flattened bottom sliver coils, and hairy sliver & roving. The bottom position sliver coils experienced the highest compressive force as discussed earlier and stickiness increased further at 8 hours of sliver storage time, resulting in weak, hairy and uneven combed sliver during the withdrawal at the speedframe. Older storage cans caused sliver quality deterioration as a result of can-spring buckling and

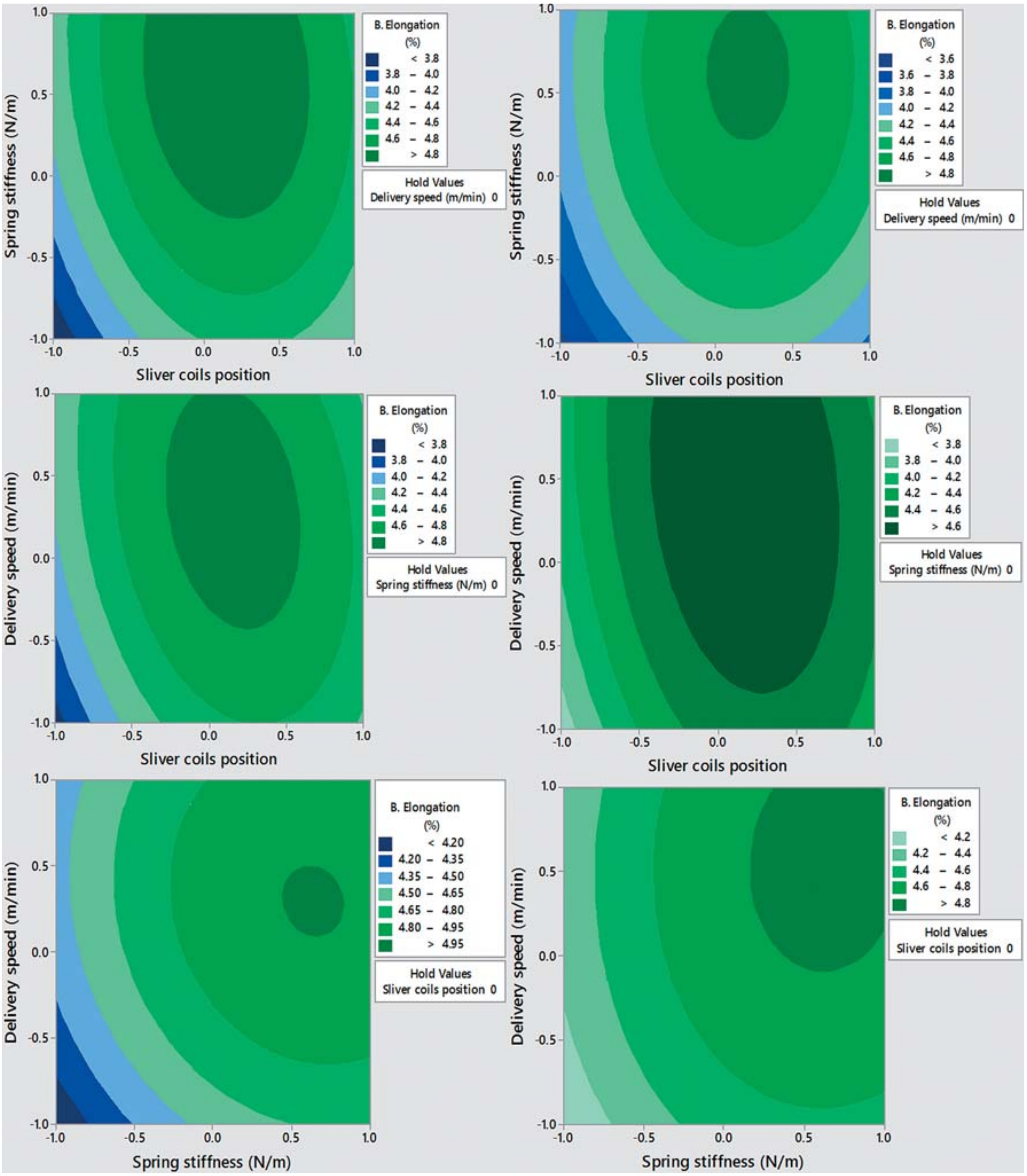

Figure 7: Effect of control factors on yarn elongation at 0 hr (left) and 8 hrs (right) storage time

sliver contact with the side wall of the container and experienced sliver splitting/stretching at the speedframe during the sliver withdrawal. The experimental results and analysis of variance revealed that the combed yarn S3 hairiness is significantly influenced by the sliver coils position, can-spring stiffness and delivery rate for the samples produced without allowing any storage time. At 8 hours of sliver storage time, the effect of the delivery rate was found insignificant, whereas the effect of the sliver coils position and can-spring stiffness was found significant at S3 hairiness. It was established that the overall combed yarn hairiness improved at 8 hours of sliver storage time as compared to that of samples where no sliver storage time was allowed, as shown in Figure 8 and vindicated by ANOVA summary.

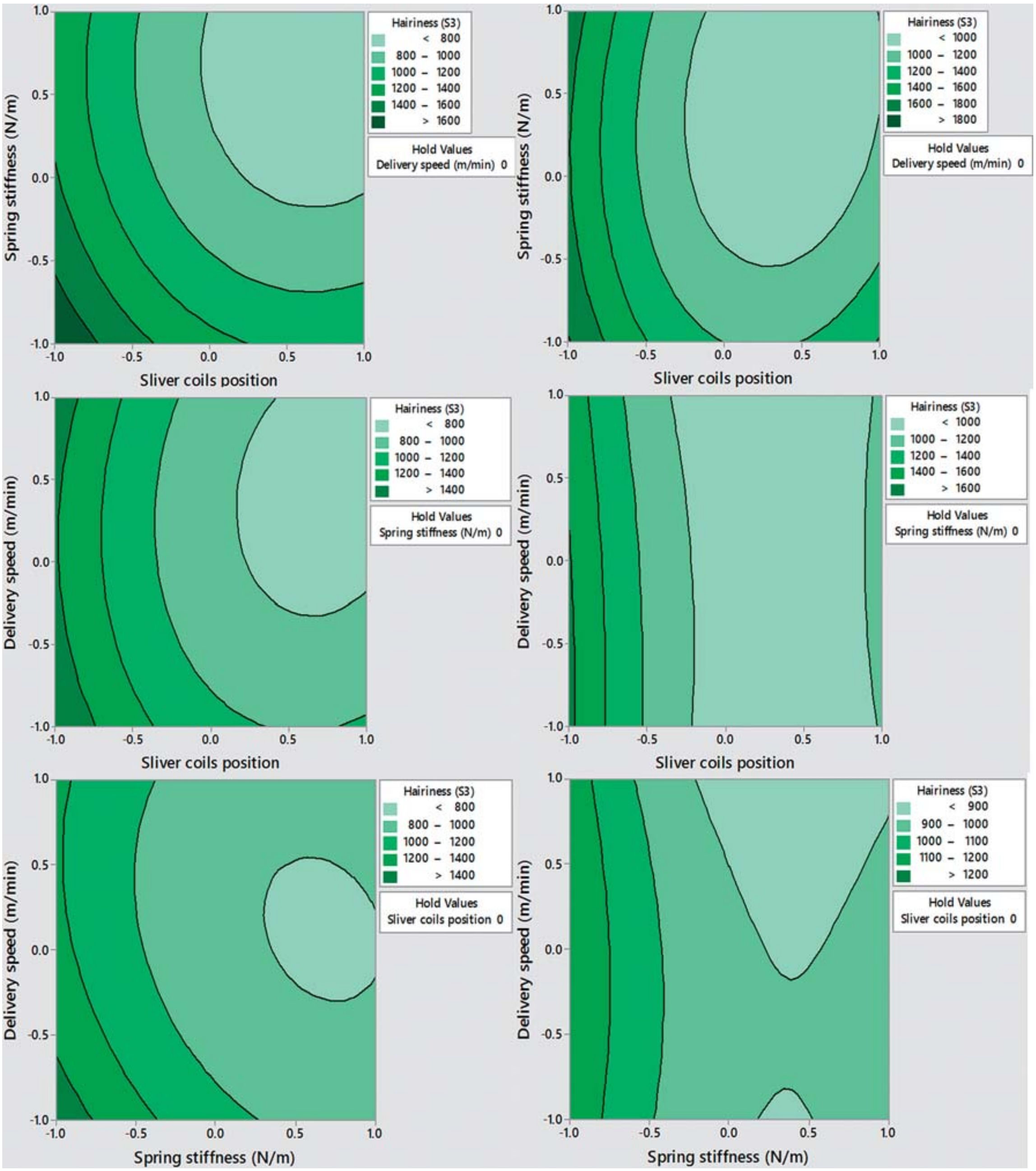

Figure 8: Effect of control factors on S3 yarn hairiness at 0 hr (left) and 8 hrs (right) storage time

3.5 Analysis of predicted versus actual values responses

The predicted versus actual value plots are merely a graphical interpretation of the analysis of variance or ANOVA, respectively. For a good fit, the actual points should be located close to the fitted line. It was found that the actual values are in a better alignment with respect to the predicted values in the case of breaking tenacity, breaking elongation and S3 hairiness for the samples produced without allowing any storage time, as shown in Figure 9. However, the predicted versus actual value plots confront non-uniform actual values distribution in the case of unevenness and imperfection for the samples produced without allowing any storage time, as shown in Figure 9.

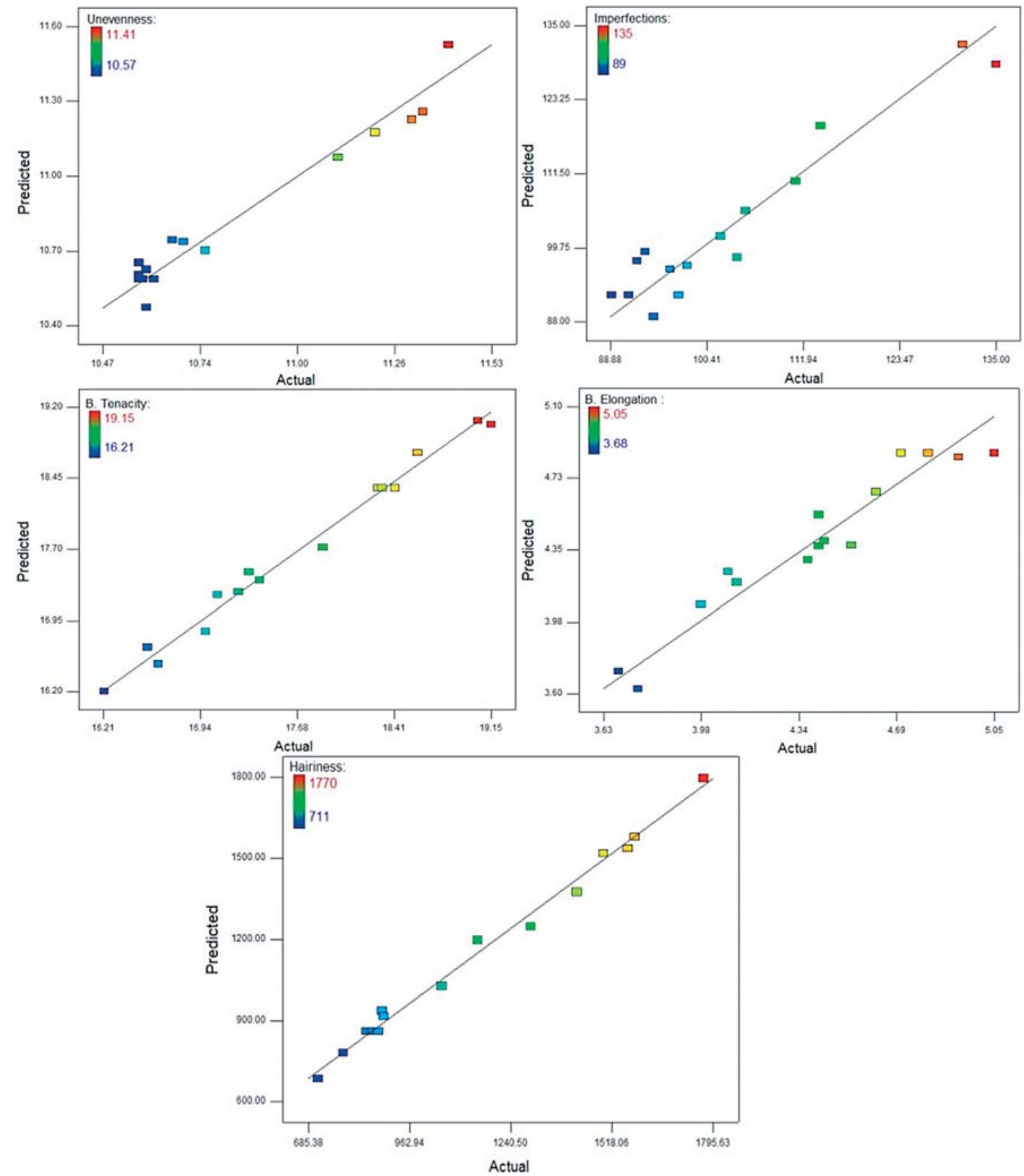

Figure 9: Actual versus predicted values of responses without allowing any storage time

The predicted versus actual value plots for the samples produced at 8 hours of storage time showed a good fit along with uniformly distributed actual values in the case of imperfections and breaking elongation, as shown in Figure 10. However, in the case of unevenness, breaking tenacity and hairiness, unevenly distributed actual values and the lack of fit was observed, which can be seen in Figure 10.

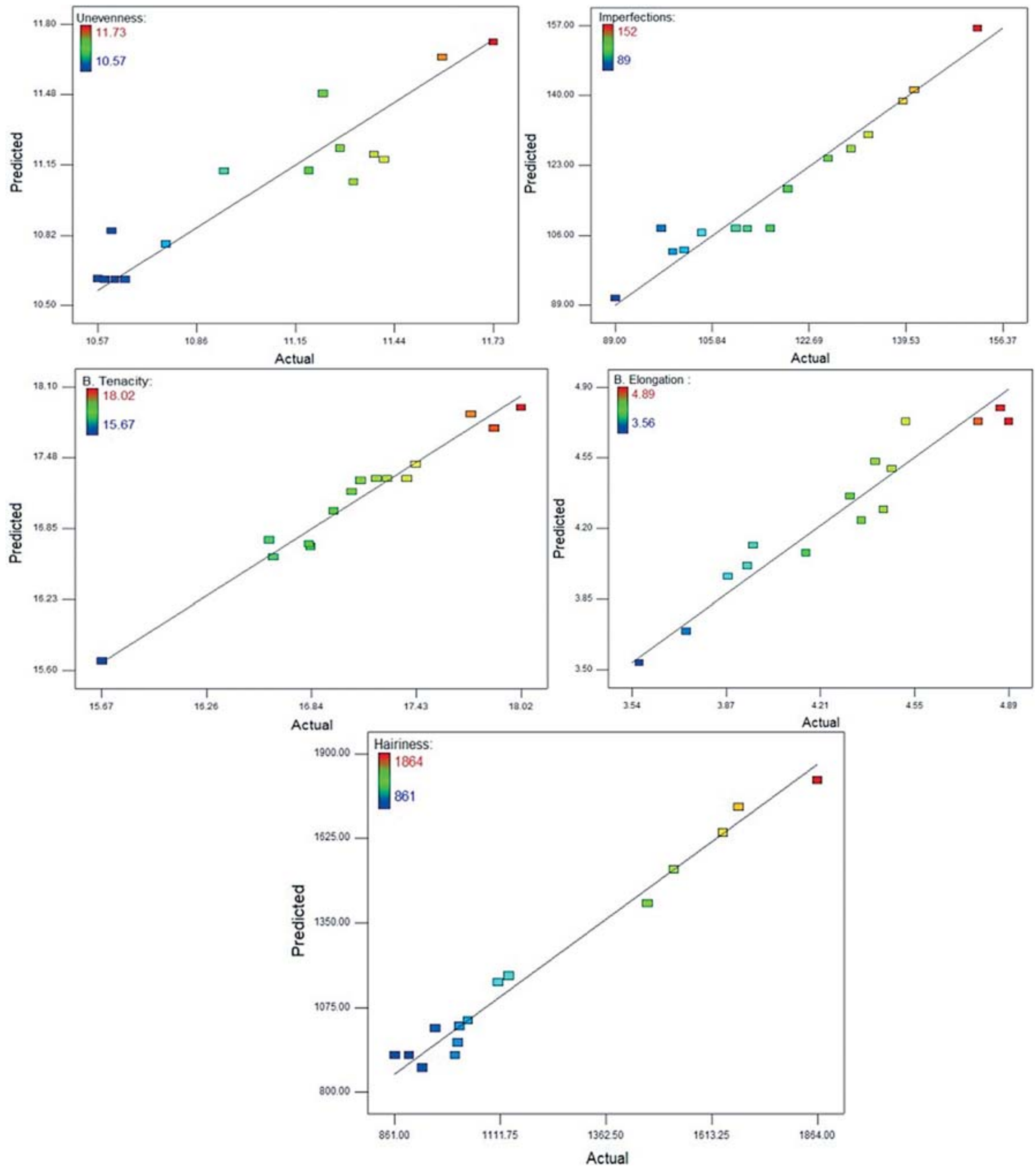

Figure 10: Actual versus predicted values of responses at 8 hours storage time

4 Conclusion

The present study was focused on investigating the effect of sliver coils position, can-spring stiffness and finisher drawframe delivery speed on combed yarn quality parameters, including unevenness, imperfections, breaking tenacity, breaking elongation and S3 hairiness index. The experimental results revealed that the combed yarn samples produced from older storage cans with the spring stiffness of 170 N/m, bottom position sliver coils, produced at 250 m/min finisher drawframe delivery speed, showed higher combed yarn unevenness, a higher number of total imperfections/km, lower breaking tenacity, relatively lower breaking elongation and higher S3 hairiness. The main reason for combed sliver quality deterioration was sliver stretching and sliver failures at the time of sliver withdrawal at the speedframe. Furthermore, the storage can-spring buckling in older cans resulted in a non-uniform distribution of the load, experienced by different position of sliver coils. The storage can-spring buckling in older storage cans was found responsible for sliver rubbing against the rough container side wall, producing hairy and weaker sliver, roving and yarn. It was found out that the samples produced from the bottom sliver coils position showed higher unevenness, more imperfections, hairy and relatively weaker resultant yarn due to improved adhesion with adjacent sliver coils, and sliver stretching and more sliver failure at the speedframe creel during sliver withdrawal. Hence, the role of sliver coils position and spring stiffness was found significant for combed yarn unevenness, imperfections, breaking tenacity and S3 yarn hairiness index. The effect of the finisher drawframe delivery rate was found insignificant for yarn unevenness and breaking elongation for the samples produced without allowing any storage time. Moreover, the effect of the delivery rate on all observed responses was found insignificant at 8 hours of storage time. Additionally, combed yarn samples produced by allowing 8 hours of sliver storage time showed higher unevenness, imperfection and S3 hairiness, and lower breaking tenacity and breaking elongation than the yarn samples produced without allowing any sliver storage time.

References

1. UGURAL, Ansel C. *Mechanical design of machine components*. *2nd ed.* Boca Raton, New York, London : CRC Press, Taylor & Francis, 2016, pp. 652−683.
2. CHESLEY, James C. *Handbook of reliability prediction procedures for mechanical equipment*. Maryland : NSWC Carderock Division West Bethesda, 2011, pp. 4.1−4.41.
3. GHOSH, A., MAJUMDAR, A. *Process control in textile manufacturing*. 1st ed. New Delhi : Woodhead India, 2013.
4. ARORA, V., SINHA, S. K. Sliver cans- an influencing factor of yarn quality. *Textile Trends*, 1998, **41**, 27−30.
5. SALHOTRA, K. R. *Spinning of manmade and blends on cotton system*. Mumbai : The Textile Association (India) Publications, 2004.
6. SINGH, Sukhvir, BHOWMICK, Niranjan, VAZ, Anand Joseph. Effect of finisher draw frame variables on combed cotton yarn quality. *Tekstilec*, 2018, **61**(4), 245–253, doi: 10.14502/Tekstilec2018.61.245-253.
7. KRETZSCHMAR, S. FURTER, D., USTER, R. *Application report - Analysis of yarns by a sophisticated classifying system*. Switzerland : Technologies AG, 2012, pp. 1−16.
8. NECKÁŘ, Bohuslav, DAS, Dipayan, ISHTIAQUE, S. M. A mathematical model of fibreorientation in slivers. *The Journal of the Textile Institute*, 2012, **103**(5), 463−476, doi: 10.1080/00405000.2011.586153.
9. DAS, Dipayan, ISHTIAQUE, S. M., DIXIT, Pragya. Influence of carding and drawing processes on orientation of fibres in slivers. *The Journal of The Textile Institute*, 2012, **103**(6), 676–686, doi: 10.1080/00405000.2011.598667.
10. NOWROUZIEH, Shahram, SINOIMERI, Artan, JEAN-YVES, Drean, FRYDRYCH, Richard. A new method of measurement of the inter-fibreforce. *Textile Research Journal*, 2007, **77**(7), 489−494, doi 10.1177/0040517507080546.
11. KLEIN, W. *Manual of Textile Technology, Vol. 3: A practical guide to combing and drawing*. Manchester : The Textile Institute, 1987, pp. 11−41.
12. ISHTIAQUE, S. M., MUKHOPADHYAY, Arunandshu, KUMAR, A. Influence of draw frame speed and its preparatory processes on ring-yarn properties. *Journal of the Textile Institute*, 2008, **99**(6), 533–538, doi: 10.1080/00405000701679632.
13. MIAO, M., NING, F., HOW, Y. Cotton-sliver strength and withdrawal-speed limit. *The Journal of Textile Institute*, 1998, **89**(3), 468−479, doi: 10.1080/00405009808658633.
14. KLEIN, W. *Manual of Textile Technology, Vol. 3: A practical guide to combing and drawing*. Manchester : The Textile Institute, 1987, pp. 43−56.
15. *Sliver handling systems*. RIMTEX 2016. Rimtex Industries, Wadhwan, Gujarat, India, <https://www.rimtex.com/>.
16. SINGH, Sukhvir, BHOWMICK, Niranjan, VAZ, Anand. Effect of can-storage parameters of finisher drawframe on combed ring spun yarn quality. *Research Journal of Textile and Apparel*, 2019, **23**(2), doi: 10.1108/RJTA-06-2018-0040.
17. SINGH, Sukhvir, BHOWMICK, Niranjan, VAZ, Anand. Influence of can-spring stiffness, delivery rate and sliver coils position on unevenness. *Journal of Textile and Apparel, Technology and Management*, 2019, **11**(1), 1−12.

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Wearable Technologies: Between Fashion, Art, Performance, and Science (Fiction)

Nosljive tehnologije: med modo, umetnostjo, performansom in znanstveno fantastiko

Scientific Review/Pregledni znanstveni članek
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Abstract

Our clothes and accessories are our primary interfaces with the world around us. In the 21st century, the technology that lives in our pockets or in our bags has changed dramatically. Today, the interactive systems that can be found almost constantly in our clothes are so close to our body that they sometimes actually feel like a part of us. Electronic devices are getting tinier and can be bought ready-made for any purpose. Power-supply solutions are smarter and wireless technologies allow communication without cables. Wearable technology is becoming widely used in healthcare, care for the elderly and wellness, in the military, in workwear and sportswear for added security or performance characteristics, in sci-fi and fantasy movies and big-arena entertainment, and in award shows or pop concerts for its spectacular visual effects. Through technological advances, the most innovative designers and artists re-evaluate the very basic premises of a dressed body, such as weight, scale and texture or movement. They demonstrate that design is not just about the visual: clothes can also be stimulating to touch, hearing, smell and taste. Wearable technology can turn clothing into a multi-sensorial experience and make it drift between categories. Wearable technology can be perceived as a body architecture, a second skin, nonmaterial clothing, a personal scenography or display, a body extension, an interactive or emotional garment, etc. Some of the most important examples of wearable technology were analysed in this research. They were divided into three different categories according to a garment's principal technological concept or function as it relates to material and external and internal stimuli, such as movement, light, sound, touch, sight, smell, taste, biometrics and emotions. It was concluded that garments act as a bridge between visual, physical and perceptual experience, and provide the wearer and onlooker with a kinaesthetic, proxemic and haptic experience. Since the late 1990s, many projects devised within the field of fashionable technology have a strong performative connotation, as they move, change shape, or emit light, sound or scents. It wasn't until the last decade, however, that Wearable technology designers really began to explore the potential of clothing as social interaction, emotional sensing and biomimetics.
Keywords: wearable technologies, responsive, active, interactive garments, emotional sensing

Izvleček

Naša oblačila in dodatki so naši primarni vmesniki za svet, ki nas obdaja. Tehnologija, ki jo imamo v žepih in torbah, se je v 21. stoletju dramatično spremenila. Komunikacijski sistemi, ki danes skoraj vedno naseljujejo naša oblačila, bivajo tako tesno ob našem telesu, da se včasih zdi, da so del nas samih. Elektronski deli postajajo čedalje manjši, kupimo jih lahko že za katerikoli namen, napajanje je razrešeno elegantno in brezžične tehnologije omogočajo komuniciranje brez kablov. Nosljive tehnologije so zaradi svojega spektakularnega vizualnega učinka čedalje bolj

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prisotne v zdravstvu, oskrbi starejših in velnes centrih, v vojaških, delovnih in športnih oblačilih za dodatno zaščito in boljšo zmogljivost, znanstvenofantastičnih in domišljijskih filmih, na stadionskih in gala prireditvah ali pop koncertih. Z napredkom tehnologij najbolj izvirni oblikovalci in umetniki na novo vrednotijo najosnovnejše predpostavke oblečenega telesa, kot so teža, merilo, tekstura ali gibanje. Kažejo nam, da pri dizajnu ne gre le za vizualno, oblačila lahko stimulirajo tudi dotik, sluh, voh in okus. Oblačilne tehnologije lahko spremenijo oblačilo v veččutno doživetje, ki lahko drsi med različnimi kategorijami. Oblačilne tehnologije lahko dojemamo kot arhitekturo, osebno scenografijo, drugo kožo, zaslon, nematerialno oblačilo, podaljšek telesa, interaktivno ali čustveno oblačilo … V preglednem članku so razčlenjeni nekateri najpomembnejši primeri oblačilnih tehnologij. Glede na glavno tehnološko idejo ali funkcijo samega oblačila v povezavi z materialom oziroma zunanjimi ali notranjimi dražljaji, kot so: gib, svetloba, zvok, dotik, vid, voh, okus, biometrija in čustva, so razdeljeni v tri skupine. Ugotovljeno je bilo, da je obleka most med vizualno, fizično in zaznavno izkušnjo, ki uporabniku in gledalcu zagotavlja kinestetično, proksemično in haptično doživetje. Od poznih devetdesetih let prejšnjega stoletja ima veliko projektov na področju modne tehnologije velik performativni pomen, saj se oblačila premikajo, spreminjajo obliko, oddajajo svetlobo, zvok ali vonjave, vendar so šele v zadnjem desetletju oblikovalci nosljive tehnologije resnično začeli raziskovati potencial oblačil kot družbene interakcije, čustvenega zaznavanja ali biomimetike.
Ključne besede: nosljive tehnologije, odzivna, aktivna in interaktivna oblačila, čustvena zaznava

1 Introduction

Our clothes and accessories are our primary interfaces with the world around us. In the 21st century, the technology that lives in our pockets or in our bags has changed dramatically. Today, the interactive systems that can be found almost constantly in our clothes are so close to our body that they sometimes actually feel like a part of us. Electronic devices are getting tinier and can be bought ready-made for any purpose. Power-supply solutions are smarter and wireless technologies allow communication without cables. Wearable technology (WT) is becoming widely used in healthcare, care for the elderly and wellness, in the military, in workwear and sportswear for added security or performance characteristics, in sci-fi and fantasy movies and big arena entertainment, and in award shows or pop concerts for its spectacular visual effects.

Through technological advances, the most innovative designers and artists re-evaluate the very basic premises of a dressed body, such as weight, scale and texture or movement. They demonstrate that design is not just about the visual: clothes can also be stimulating to touch, hearing, smell and taste. WT can turn clothing into a multi-sensorial experience and make it drift between categories. WT can be perceived as a body architecture, a second skin, nonmaterial clothing, a personal scenography or display, a body extension, an interactive or emotional garment, etc.

The objective of the presented research was to study, analyse and classify WT according to the factors that best define them. The content analysis and synthesis of key cases were applied for that classification.

2 WT: Fashion, Performance, Art or Science (Fiction)

According to Susan Elizabeth Ryan [1] (2014, p. 96), the term 'wearable technology' or WT applies to work that is functional in application and potentially commercial in distribution or experimental and conceptual in nature to aid the awareness of embodiment. Many of the works cited here are what she calls 'critical WT' or 'critical dress', even when they are the result of experimentation with technology as a means of expression for fashion designers, such as Hussein Chalayan [2], Anouk Wipprecht [3], Ying Gao [4] or CuteCircuit [5], to name but a few. The majority of those projects only exist as artworks or research prototypes, with a non-commercial content and clear conceptual and performance character. They are exhibited in art and fashion galleries and museums, or are presented at trade fairs or academic conferences and workshops.

In the last decade, wearable technology appears to be a major trend in fashion. It is, however, far from something new, innovative, avant-garde or the invention thereof. There are examples of wearable electronics from the 1960s, 1970s and 1980s, and most of them were created by fine artists and performers, not by fashion designers. Some of them, such as Atsuko Tanaka [6], Rebecca Horn [7] Stelarc [8], Jana Sterbak [9], or Marcel·lí Antúnez Roca

[10] created their art pieces as direct critique of fashion system or the mainstream canons of beauty. The study of wearable computers was born in the realm of universities and research labs some 60 years ago, but created its platform through new artistic movements like performances, events or body art and festivals such as Ars Electronica, which has been bringing the audience closer to the artist since the 1980s. However, it took someone really visionary to combine heavy, large and rigid computers and lightweight, soft, sensuous textiles. In the mid-1990s, Maggie Orth and Rehmi Post [11], who led a team of researchers at MIT's Media Lab, began to explore how digital electronics could be integrated into clothing by using sewable conductive materials. In 2007, Leah Buechley created the first flexible Lilypad Arduino circuit [11].

Wearable technology is, in its essence, anti-dress and anti-fashion. WT's ultimate goal is to make clothing durable, self-cleaning and adaptable to all situations or seasons. Ryan [1] (2014, p. 105) claims: 'WT rehearses an age-old dialogue between society and the body that proposes a process of invisibility based on an ideal of pure functionality and pure information, and ultimately a uniformity of dress.'

The synergistic link between fashion and technology is beneficial for both elements. Fashion gives WT a bigger projection, informs a wider audience of its potentials and can even create new commercial niches, which in turn can result in funding for new research. Bradley Quinn [12] (2012, p. 12) asserts that technology and fashion are a perfect match: 'when associated with garments, which are by nature portable, wireless technology becomes even more mobile, and as technologized fashions wirelessly connect garments to remote systems, they extend both their own functionality and technology's reach. Together, the two are finding new uses for traditional materials and techniques, while also inspiring new types of tailoring and high-tech fashion fabrics.'

Ryan [1] (2014, p. 11) observes that: 'More and more designers and artists utilize garments empowered with their own abilities to act or react, to reveal the moment-by-moment nature of dress and the ironies in our hybridized, digital/physical relations.' They believe that clothes are as important as the way in which they are represented. Garments made of responsive materials or embedded with sensors and actuators that emit sounds or light or create physical movement have a clear performance aspect. WT sometimes gives clothes a form of scenography, narrative or a character, which can make for a great marketing tool. For this reason, many fashion collections feature at least one unwearable WT piece that makes catwalk theatrical and ends up as a spectacular promotional photograph.

According to Johannes Birringer [13] (2008, p. 215), the role of fashion and clothing directly relates to the complex social and theatrical concept of 'performance'. Many designers, engineers, artists and performance-artists base their work on the relationship between a performing body, material, movement and the observer. By redefining the meaning of a dressed body, they are merging the boundaries of theatrical performance, fashion and contemporary art, resulting in new approaches, hybrid practices and new terminology, such as fashionable technology, scientific couture, wearable art, conceptual clothing and critical costume.

Some artists and textile designers experiment with immaterial [14] and disintegrating clothing [15] made using projections [16], smoke [17], gel, balloons, bodily fluids [18], hair and garbage. Some, apart from searching for a material, aesthetic and somatic experience, base their work on exploring key scenographic elements related to costume: time, space, movement, light and sound, which give identity to an otherwise inanimate garment.

By examining the performative qualities of alternative materials, they question the spatial and temporal limits of body/dress or body/costume. Alexandra Cabral and Manuel Figueiredo [19] (2014: 2431) state that 'both space and garments become fictional projections of body limits, as they are conceptual interventions and physical extensions of a performer'. Sofia Pantouvaki [20] (2014: 117) speaks of a 'scenographic costume' or 'spatial costume', while Jessica Bugg [21] (2014: 39) calls it 'body located scenography' and Dorita Hannah [22] (2014: 15) discusses costume as 'a spatial body-object'.

Johannes Birringer and Michèle Danjoux [23] (2009, p. 5) said that interdisciplinary advances in smart materials and wearable design will result in 'a future of sensing/communicating clothing that can express people's personalities, needs and desires, or augment social dynamics through the use of wearables as 'theatre' and as emotional 'tools'.' They distinguish between two categories of wearables used in a performing sense: *intelligent* (reactive materials and garments with shape-changing or display character) that do not require particular performance techniques, and *interfacial* (sensing and actuating) garments that interact with the performer or/and audience. Similarly, Michaela Honauer [24] (2017, p. 281) speaks of *active* and *interactive* costumes.

Artists have been using WT as an expressive and critical tool for decades, especially when dealing with themes of privacy, disembodiment, invisibility, and augmented and virtual realities. Birringer and Danjoux [23] (2009, p. 5) explain: 'the artistic experimentation with smart technologies is of course not market-oriented and has no end-user. Rather, the mobilization of smart technology concerns sensorial experience and expression (involving transformations of the performer-audience relations), a more experimental and playful adaptation of the digital medium as a wearable medium.'

New media artist Melissa Coleman (in Rebeccah Pailes-Friedman [25], 2016, p. 13) asserts: 'One of the functions of fine art is to create a discourse around subjects that are already happening in society, or that are looking to start happening. And anything related to textiles is never separated far from issues around body.'

No matter how advanced the technology, the point is to connect people, just like fashion and clothing. Birringer and Danjoux [23] (2009, p. 5) speak of the Japanese notion of *kansei* (emotion design) that 'implies a stronger emphasis on the wearable as a social medium, capturing user subjectivity and intimacy.' Fashion tech designer Anouk Wipprecht says (in Kaplan [26], 2015): 'The position that technology has in our society – the role to please us – will get more and more intimate. [...] As technology crawls closer to the skin we will need to rethink and recreate the relation that we have towards technology.'

Back in 1999, Stefano Marzano, the CEO of Philips Design Probes, suggested (in Ryan [1], 2014, p. 112) that the fashion industry must be transformed so that clothing design is no longer simply a choice of colours and styles, but a choice of functions, and the technology industry will have to learn to think emotionally, until functional applications can be incorporated directly into our bodies.

3 Classification of WT

Some of the most characteristic examples of wearable technologies are presented below. This research focused on the content analysis and categorisation of WT, which until now have not been implemented in this form. The presented classification represents an innovative approach to understanding the importance, usefulness and application of WT.

Garments are defined by the material from which they are made. They represent the frontier and the connection between the body and the environment around it. They have an internal (personal) and an external (social) side.

The examples presented here were chosen for the technological concept behind the garment. Some of the examples are made of responsive materials, while some of them are active. The majority of examples, however, are interactive garments. All examples have been classified into one of three categories: material, external stimuli or internal stimuli. Each category has several subcategories: responsive material and 'immaterial' garments in the material category; movement, light, sound and touch in the external stimuli category; and biometrics/emotional sensing and biomimetics in the internal stimuli category.

Many of the examples could be classified to two or three different categories, as they have diverse functions and could be used and interpreted in different ways. What all of them have in common is that in a few years' time all of these garments will be outdated and outshined by more innovative garments, and forgotten.

2.1 Material

Responsive material

- Material changes its colour or transparency when lit or touched, and due to body heat or sweat, or drops of water. It glows in the dark, changes texture or shape, emits light or sounds, conducts electricity and data, and stores energy.
- Hydrochromic ink, thermochromic ink, glow in the dark ink, conductive paint, shape-memory alloy, disintegrating materials, mechanically collapsible textures, phase-changing materials, stimuli-responsive polymers, printable circuits that transfer data, etc.
- Examples:
  - Catalytic Clothing (Herself): Material sucks and eliminates pollutants from the air surrounding it; dress in the form of a lung (Figure 1, [27]).
  - DuoSkin: Tattooed circuit transfers data and lets the wearer control their devices directly from their skin (Figure 2, [28]).


Figure 1: Helen Storey & Tony Ryan. Catalytic Clothing (Herself), 2010 [27]

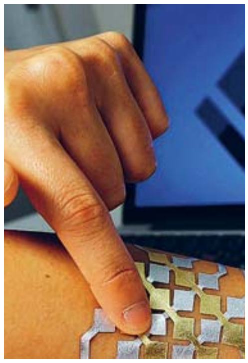
Figure 2: MIT Media Lab / Cindy Hsin-Liu Kao, Christian Holz, Asta Roseway, Andres Calvo, Chris Schmandt. DuoSkin, 2016 [28]

'Immaterial' garments

- Immaterial garments create an illusion of immateriality.
- Garments are made by light, smoke, mirrors, two-phase foils, projections, motion-tracked body mapping, hologram, and virtual and augmented reality.
- Examples:
  – Smoke dress: Dress is activated by proximity sensors. When someone steps into the personal space of the wearer, the dress creates a veil of smoke. By obscuring personal boundaries, the dress creates a dialogue between the wearer and their surroundings. The smoke can be scented so anyone can smell and taste the dress as they inhale it (Figure 3, [17]).
  – Apparition: A performer wears a motion-tracking body projection mapping, which moves in unison with their dancing body. Immaterial performance costumes can be the most sustainable option: they are comfortable, cheap to make, easy to maintain and do not occupy storage space (Figure 4, [16]).
  – Apparel VO.9A: This garment is an augmented reality prototype. The 'wearer' will neither wear nor physically feel the garment. They and the onlookers will only see or feel it with help of special glasses or a special glove. It embodies the concept of the body as a continuously changeable display that reacts to the wearer's biometrics and social media profiles in real time. The designer does not have to deal with textiles and construction limitations anymore: shape, volume and texture are replaced by graphics and animation (Figure 5, [14]).

2.2 External stimuli

- Input comes from outside of the garment (changes in the garment activated by proximity, movement, light, projection, sound, voice, gaze and touch).

Movement

- Moving dress, vehicle dress, flying dress, disappearing dress, dress moving as if it were a part of


Figure 3: Anouk Wipprecht. Smoke dress, 2011-13 [17]

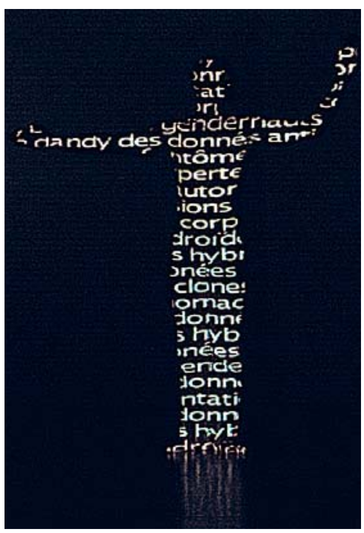

Figure 4: Klaus Obermaier. Apparition, 2004 [16]


Figure 5: Normals. Apparel VO.9A, 2012 [14]

the body, lighting dress, instrument dress, dress as choreography, etc.

- Sensors: movement, proximity, accelerometer, gyroscope, piezo, tilt, ultrasound, infrared, microphones, eye-tracking cameras, motors, speakers, LEDs, EL wires and panels, inflatables, drones, etc.
- Garments that are activated by the movement of the wearer. Garments that start to move (get, bigger, smaller, change shape and texture, etc.) when activated by some external stimuli, usually not controlled by the wearer. A garment that moves, but it is the garment that wears the performer (who does not touch the ground); controlled by the wearer or from a distance.
- Examples:
  – One hundred and eleven: Dress progressively disappears into a hat using a motor (Figure 6, [29]).

Figure 6: Hussein Chalayan & Adam Wright. One hundred and eleven, 2007 [29]

  – Butterfly dress: Dress transforms or partially disintegrates as someone moves towards it. Forty butterflies start to flutter and then fly away, activated by a proximity sensor or via a mobile device that communicates with the dress over a wireless network (Figure 7, [15]).

Figure 7: Ezra & Tuba Çetin. Butterfly dress, 2015 [15]

  – Volantis, world's first flying dress: Remotely controlled flying platform dress is moved by six large drones (Figure 8, [30]).

Figure 8: Studio XO. Volantis, worlds first flying dress, 2013 [30]

Light

- Garments are activated by light or other external stimuli such as voice, ambient sound, touch or gaze that makes garments emit light or pre-programmed or interactive images.
- Dress that lights up a wearer's personal space, dress that turns on/off ambient lights, dress as a display, dress as a projection screen, dress as a projector, dress as a text message, dress as moving pictures, etc.
- Examples:
  – (No)where (Now)here: Dress turns off lights and illuminates when someone looks directly at it (Figure 9, [31]).

Figure 9: Ying Gao. (No)where (now)here, 2013 [31]

  – Bono's Laser jacket: The jacket is equipped with dozens of laser spot lights that are projected on audience members individually, thus connecting a performer with a spectator on a personal level (Figure 10, [32]).

Figure 10: Moritz Waldemeyer. Bono's Laser jacket, 2010 [32]

– Twitter dress: Dress allows one to wear online comments. Full-colour LED pixels show the most popular tweets about the dress, the wearer or the event in real time (Figure 11, [33]).

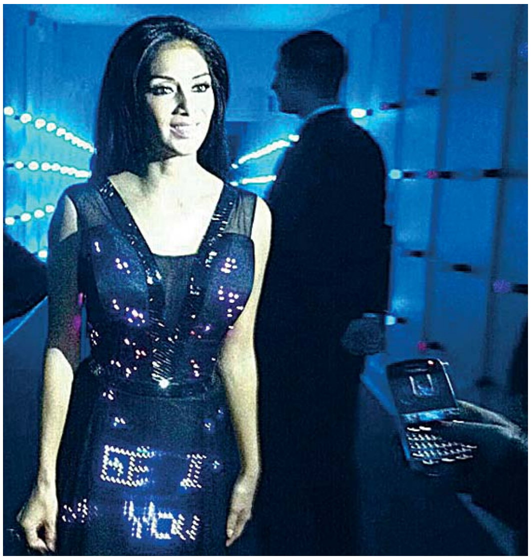

Figure 11: CuteCircuit. Twitter dress, 2012 [33]

Sound

- Garments are activated by sound, voice, talking, singing, clapping, ambient sounds, music, touch or proximity to make them emit sounds (amplified, in real time or pre-recorded, interactive).
- Dress as an instrument, microphone, speaker, etc.
- Examples:

– Sonifica: A wearable bustier and a prosthetic leg turn multimedia performance artist Viktoria Modesta's body into an instrument. Both pieces use open-source hardware and software that recognises gestures, and a six-axis accelerometer and gyroscope to track movement and interact spatially and sonically with her environment and participating audience, creating an intimate and collaborative show (Figure 12, [34]).

Figure 12: Viktoria Modesta & Anouk Wipprecht. Sonifica, 2017 [34]

– Soundshirt: Shirt helps deaf people feel music thanks to 16 micro actuators embedded in the fabric of the garment. These actuators receive the music that the orchestra is playing wirelessly and in real-time. Transformed into data, for example, violins can be felt on the arms and drums on the back. An entire composition comes to life as a series of haptic (touch-like) sensations across the torso of the person wearing the shirt. 'What you hear... I can feel!' Kassandra Wedel (in CuteCircuit [35] 2016), deaf dancer and actress, (Figure 13, [36]).

Figure 13: CuteCircuit. Soundshirt, 2016 [36]

Touch

- Garments are activated by human touch, raindrops, proximity and haptic touch from a distance.
- Dress as a music player, dress as a text messenger, dress as a flickering lamp, dress as a hug from a distance, etc.
- Examples:
  - Hugshirt: Shirt delivers a 'hug' from a distant hugshirt using Bluetooth and sensor technology. By applying pressure to certain points on the body, the shirt recreates the haptic sensation of the touch, warmth and emotion of a hug. It is designed to be worn by both caller and receiver, and represents the physical dimension that phone-based digital communication lacks (Figure 14, [37]).
  - Puddle jumper: When raindrops hit the coat, the sensors activate EL lamps. A flickering pattern of illumination mirrors the rhythm of rainfall (Figure 15, [38]).

Figure 14: CuteCircuit. Hugshirt, 2004 [37]

Figure 15: Elise Co. Puddle jumper, 2001-02 [38]

  - Coded sensation: Garments that are made from fabric that carries information from magnetic tape cassettes serve as a music player. Music, stories or poems start to play when the surface of the garment is touched by a glove device (Figure 16, [39]).

Figure 16: Martin Rille. Coded sensation, 2009 [39]

2.3 Internal stimuli

- Input comes from the inside of the garment, while changes in the garment are activated by the wearer's biometrics.
- Garments are activated by breathing, heartbeat, muscle movement, blinking of the eyes, voice vibration, perspiration, skin pH and EEG brain activity to make them move, blink, glow, make photos, or emit light, sound, music, smoke, scents or liquids.
- Concepts of multi-sensory surfaces and social interaction design: a garment acts in accordance with the wearer's psychological and emotional state. For this reason, it seems to act on its own and as if it were part of the wearer's skin or body.
- Technically, this type of garments is much more advanced and requires many more electronic components, programming and sensors: movement, proximity, muscle strain, ultrasound, infrared, breathing, heartbeat, perspiration, skin temperature, brain activity, microphones, eye-tracking cameras, motors, speakers, LEDs, EL wires and panels, inflatables, etc.

Biometrics and emotional sensing

- Garments are activated by somatics, small gestures, breathing, heartbeat, skin temperature, perspiration, muscle tension, voice recognition or visual focus (all are indicators of anxiousness, insecurity, blushing, unease, stress, distraction, lying, etc.) to make them light up, change colours, inflate or deliver an electric shock.
- Examples:
  - The holy dress: The dress starts to glow and increases in intensity using data from a speech recognition system and voice stress analysis. When a lie is detected, the garment lights up fully and delivers an electric shock to the wearer as punishment. In this way, the garment trains the wearer to live an honest life and become a better person (Figure 17, [40]).

Figure 17: Melissa Coleman, Leonie Smelt & Joachim Rotteveel. The holy dress, 2016 [40]

- Smart second skin dress: This therapeutic garment is integrated with a wireless sensor network that uses nanotechnology and microfluidics. It senses the wearer's body heat and other indicators of stress, and releases aromas to boost the limbic system in the brain or deodorant when sweat is detected. The dress, conceived as a second skin, can alter mood, encourage sleep or energise action, increase self-esteem and stimulate the imagination (Figure 18, [18]).

Figure 18: Jenny Tillotson & Adeline André. Smart second skin dress, 2003 [18]

- Trans-For-M-Otion: The garment immediately reacts to how the wearer is feeling in a changing environment. Heartbeat, body temperature, respiration and muscle-tension are sensed and processed. When the wearer feels anxious or insecure, small air cells in the garment fill up like little cushions, so that the garment immediately fits closer to the body and the wearer feels safe and protected. LED lights also respond directly to the wearer's movements and emotion to soothe them (Figure 19, [41]).

Figure 19: Eunjeong Jeon. Trans-For-M-Otion, 2010 [41]

Biomimetics

- Garments are activated by proximity, increased heart rate, breathing, perspiration, body temperature, or an observer's facial expression to make them move, inflate, glow, and emit light and sound.
- Garments mimic natural forms, animal movements and behaviours, such as an animal raising its fur to make it look bigger or attack in self-defence.
- Examples:
  - Robotic spider dress: A device worn on the shoulders, which consists of six mechanical spider legs, acts on behalf of the wearer and can attack using the same viewing angle as the wearer when someone enters their personal space. Using wireless biometric signals from proximity and breathing sensors, the system makes inferences based on the stress levels in the wearer's body and can differentiate between 12 different states of behaviour. The system knows how the wearer feels and can adapt its behaviour to those feelings. The system's own opinion is based on the logic and data programmed through social studies and environmental psychology. In this way, the robotic spider dress becomes a part of the person, instead of something separate that stands alone (Figure 20, [42]).

Figure 20: Anouk Wipprecht & Daniel Schatzmayr. Robotic spider dress, 2014 [42]

  - Opale: The dress senses aggression and bristles its 'fur' as a defence mechanism or as a form of intimidation when under threat, or purrs when stroked. Inspired by cat, dog or mice fur, the outfit is equipped with facial tracking technology, which detects an observer's facial expressions (happiness, sadness, surprise, anger or neutral), an interactive pneumatic inflatable system (six motors and CO_2 capsules) and a forest of fibre optics embedded in silicon that react by movement and sound (Figure 21, [43]).

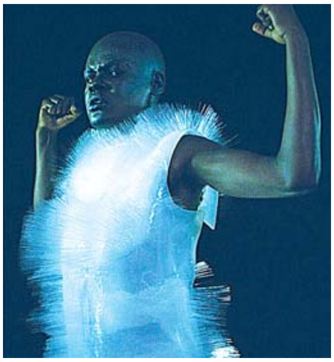

Figure 21: Behnaz Farahi. Opale, 2017 [43]

3 Discussion

Through existing literature and internet research, the best-known and innovative examples of technology-embedded clothing from the last 30 years were gathered to analyse the increasing interdisciplinary relationship between fashion, performance, art and science, and to identify some characteristics and draw conclusions about the current state of WT. Two thirds of the examples were created by women. Only 35% of the examples came from fashion (presented as a part of a fashion collection, catwalk or red-carpet event), while 25% of examples were presented in an art gallery or museum, 20% on stage, in musical concerts or theatre performances, and 20% were conceived as a scientific research prototype or are still in the experimental stage.

The most important characteristic of wearable technologies is team collaboration, as WT is an interdisciplinary undertaking. Teams are formed by designers, technologists and engineers. Many designers today have backgrounds in science or technology, fashion, interface design or art, but still require help and advice from material or biomimetics scientists, electronic and robotics engineers, nanotechnologists, neurologists or anthropologists.

Collaborations between Hussein Chalayan, Moritz Waldemeyer [44], Adam Wright [45] or Karolina Cengija [46] are some of the most fruitful. The Chalayan-Cengija collaboration is just one of many exceptions to the stereotype of multidisciplinary teams, combining the traditionally female practice of dress-making with the previously male-dominated disciplines of technology and materials science. An interesting phenomenon is actually occurring: a new breed of fashion designers/electronic engineers is emerging and will break gender barriers forever. Young women such as Anouk Wipprecht [47], Becca McCharen [48], Kate Hartman [49], Sabine Seymour [50] and Limor Fried [51] have their own hi-tech fashion brands, lead their own WT labs or electronic supply companies, and are paving the way for the next generation of women fashion tech designers.

Another aspect of collaboration is that in order to ensure the best use and reach of their work, WT artists and studios are joining forces with some of the most famous and most avant-garde pop stars, such as Lady Gaga, Björk, Viktoria Modesta, Black Eyed Peas, Pet Shop Boys and other celebrities for their music videos, tours, advertising campaigns and red carpets events. In this way, WT takes advantage of three different media channels to reach the masses: fashion, music and art/design.

However, it is in large-venue concerts where WT is tested to its very limits, not just for its spectacular effects, but above all for its functionality, durability, safety and comfort. It is these performers who challenge the designers to create ever more innovative designs for their next tour. WT is a great tool to connect with the masses in big-stage productions where the audience can be hundreds of meters away from the performer, as 'interactive and responsive costumes can transform performance on both a larger stage scale, as well as the intimate and relational scale of the costume.' (Pantouvaki [52], 2014, p. 193).

Another important characteristic of WT is the fact that electronic devices are becoming smaller and cheaper every day, and that there is an open-source coding community willing to share their knowledge free-of-charge. Anyone interested in working with WT with a minimum budget and minimum sewing and programming skills can create a great and innovative design or artwork. There are also books, online blogs and tutorials for beginners and professional WT makers. Fashionable technology entrepreneur Sabine Seymour (in Quinn [12], 2012, p. 164) believes in the model of open innovation and argues that 'it is important for creators to have access to the new materials, processes and methodologies that are developed by such corporate entities. Safeguarding and restricting access to new techniques do not produce innovation but rather hinder it. Not only is creativity stifled, but also the potential for financial returns of investment to the investors is limited.'

There are still many challenges and limitations for WT. To stay innovative, the fashion world requires deeper knowledge about tools, materials and manufacturing, but very few designers have total access to the latest advances in technologies. Trend expert Anne Marie Commandeur (in Quinn [12], 2012, p. 226) argues that technology is advancing rapidly in all areas of design, except fashion and that 'textile technology, textile designs, garment manufacturing, finishers, fashion designers and now scientific researchers work without a common platform that would enable them to build bridges between these processes.' WT designer Becca McCharen of Chromat (in Kaplan [53], 2015) claims that the biggest problem is getting their designs into production. She says: 'We know we can do amazing things with materials, we know it enables a completely new aesthetic … [but] it's getting it into the hand of the consumer, and that's a manufacturing and distribution problem'.

Short deadlines for creating seasonal collections and the quick reversal of trends often discourage fashion designers from transforming their research into new materials and aesthetic and performative values that result in wearable technology. Sometimes, designers simply show no interest in wearable technologies. Conceptual fashion designer Ying Gao (in Pailes-Friedman [25], 2016, p. 140) argues that designers themselves are not brave enough to experiment and asserts: 'We have lost this critical thinking that people have in other fields such as media design and cinema.' Moreover, there are still practical issues to be resolved: wires and batteries are not soft and do not have flexible joints, so they are still unable to stretch and bend with the body. Electronic circuits are still not tough enough to stand up to wearing, washing and repairs. With regard to wearability, the challenges faced by costume designers are even greater, as they are creating for a known end-user, the performer. The appearance has to fit metaphorically into the character played and be visible for all audience members, regardless of where they sit. In addition, costumes must be robust enough to be worn multiple times, and to be dressed or undressed quickly. They have to be durable, comfortable, safe, not too hot and allow for freedom of movement.

Another negative characteristic is the lack of criticism in WT literature. Almost every year, lushly illustrated books are published demonstrating the current state of WT and big-named "fashion" exhibitions such as Manus X Machina take place [54]. Ryan [1] (2014, p. 6) claims that 'the WT literature testifies to an enormous and growing field', but that much of its 'activity has gone untouched by historical and cultural examination.' She blames it on literature's 'consistently affirmative and advocative tone, reminiscent of marketing and journalism, and the absence of any negative remarks, or any critical perspective whatsoever.'

4 Conclusion

Clothing embedded with WT can generate a specific body-mind involvement. We can perceive clothing with all of our senses: sight, touch, hearing, smell, taste, even multi-sensory or synesthesia. Garments represent a bridge between visual, physical and perceptual experience, providing the wearer and the observer with a kinaesthetic, proxemic and haptic experience.

Since the late 1990s, many of the projects devised within the field of fashionable technology have a strong performative connotation, as they move, change shape, or emit light, sound or scents. It wasn't until the last decade, however, that WT designers really began to explore the potential of clothing as social interaction, emotional sensing or biomimetics.

The mass production of WT garments will probably never occur, and although it may have sounded like science fiction 20 years ago, somewhere some teenage cosplayer is 3D printing materials and clothes that we saw as a crazy futuristic idea in a movie, comic or video game right now in their own room.

References

1. RYAN, Susan Elizabeth. *Garments of paradise: wearable discourse in the digital age*. Cambridge, Massachusetts, London, England : The MIT Press, 2014.
2. Dezeen. *Hussein Chalayan* [online], [accessed 25. 3. 2019]. Available on World Wide Web: <https://www.dezeen.com/?s=hussein%20chalayan&hPP=40&idx=vetg_livesearchable_posts&p=0&fR%5Bpost_type_label%5D%5B0%5D=&is_v=1>.
3. Dezeen. Anouk Wipprecht [online], [accessed 25. 3. 2019]. Available on World Wide Web:

<https://www.dezeen.com/?s=anouk%20wipprecht&hPP=40&idx=vetg_livesearchable_posts&p=0&fR%5Bpost_type_label%5D%5B0%5D=&is_v=1>.

4. Dezeen. Ying Gao [online], [accessed 25. 3. 2019]. Available on World Wide Web: <https://www.dezeen.com/?s=ying%20gao&hPP=40&idx=vetg_livesearchable_posts&p=0&is_v=1>.
5. Dezeen. CuteCircuit [online], [accessed 25. 3. 2019]. Available on World Wide Web: <https://www.dezeen.com/?s=cutecircuit&hPP=40&idx=vetg_livesearchable_posts&p=0&is_v=1>.
6. Artnet. Atsuko Tanaka [online], [accessed 25. 3. 2019]. Available on World Wide Web: < http://www.artnet.com/artists/atsuko-tanaka/>.
7. Rebecca Horn [online], [accessed 25. 3. 2019]. Available on World Wide Web: <http://www.rebecca-horn.de/>.
8. Stelarc [online], [accessed 25. 3. 2019]. Available on World Wide Web: <http://stelarc.org/projects.php>.
9. Artnet. Jana Sterbak [online], [accessed 25. 3. 2019]. Available on World Wide Web: <http://www.artnet.com/artists/jana-sterbak/>.
10. Marcel·lí Antúnez Roca [online], [accessed 25. 3. 2019]. Available on World Wide Web: < http://marceliantunez.com/>.
11. BAPTISTE, Jean. A brief history of electronic textiles [online], [accessed 25. 3. 2019]. Available on World Wide Web: <https://medium.com/@jeanbaptiste/a-brief-history-of-electronic-textiles-dee610be667b>.
12. QUINN, Bradley. *Fashion Futures*. London, New York : Merrell Publishers, 2012.
13. BIRRINGER, Johannes. *Performance, technology, & science*. New York : PAJ Publications, 2008.
14. Normals. Apparel V0.9A [online], [accessed 20. 3. 2019]. Available on World Wide Web: <http://mixtur.es/normals/apparel/apparelv09a/>.
15. Çetin, Ezra and Tuba. Butterfly dress [online], [accessed 20. 3. 2019]. Available on World Wide Web: <https://www.pinterest.com/pin/359513982734256288/>.
16. Obermeier, Klaus. Apparition [online], [accessed 20. 3. 2019]. Available on World Wide Web: <http://www.exile.at/apparition/photos_download.html>.
17. Wipprecht, Anouk. Smoke dress [online], [accessed 20. 3. 2019]. Available on World Wide Web: <http://streamingmuseum.org/anouk-wipprecht-what-does-fashion-lack-microcontrollers/>.
18. TILLOTSON, Jenny, ANDRÉ, Adeline. Smart second skin dress [online], [accessed 23. 3. 2019]. Available on World Wide Web: <http://ualresearchonline.arts.ac.uk/5570/>.
19. CABRAL, Alexandra and FIGUEIREDO, Carlos Manuel. Costume design: Ergonomics in performance art [online], [accessed 20. 3. 2019]. Available on World Wide Web: <https://www.academia.edu/10733833/_Costume_Design_Ergonomics_in_Performance_Art_Proceedings_of_the_5th_AHFE_International_Conference_on_Applied_Human_Factors_and_Ergonomics_2014_Jagiellonian_University_Krak%C3%B3w_Poland_>.
20. PANTOUVAKI, Sofia. Costume in the absence of the body. In *Presence and absence: the performing body.* Edited by A. Anderson and S. Pantouvaki. Oxford : Inter-Disciplinary Press, 2014, pp. 101−127.
21. BUGG, Jessica. Emotion and memory: Clothing the body as performance. In *Presence and absence: The performing body.* Edited by A. Anderson and S. Pantouvaki. Oxford : Inter-Disciplinary Press, 2014, pp. 29–52.
22. HANNAH, Dorita. Alarming the heart: Costume as performative body-object-event. *Scene,* 2014, **2**(1+2), 15–34, doi: 10.1386/scene.2.1-2.15_1.
23. BIRRINGER, Johannes, DANJOUX, Michele. Wearable performance, [online], [accessed 20. 3. 2019]. Available on World Wide Web: <http://bura.brunel.ac.uk/handle/2438/5681>.
24. HONAUER, Michaela. Designing (inter)active costumes for professional stages. In *Smart textiles.* Edited by Schneegass, S. and Amft, O. Cham : Springer, 2017, pp. 279–299, doi: 10.1007/978-3-319-50124-6_13.
25. PAILES-FRIEDMAN, Rebeccah. *Smart textiles for designers: Inventing the future of fabrics.* London : Laurence King, 2016.
26. KAPLAN, Ken. Robotic spider dress powered by Intel smart wearable technology [online], [accessed 20. 3. 2019]. Available on World Wide Web: <https://iq.intel.com/smart-spider-dress-by-dutch-designer-anouk-wipprecht/>.
27. STOREY, Helen, RYAN, Tony. Catalytic Clothing (herself) [online], [accessed 20. 3. 2019]. Available on World Wide Web: <http://sustainable-fashion.com/projects/catalytic-clothing/>.

28. HSIN-LIU KAO, Cindy, HOLZ, Christian, ROSEWAY, Asta, CALVO, Andres, SCHMANDT, Chris. DuoSkin [online], [accessed 20. 3. 2019]. Available on World Wide Web: <https://www.xataka.com/investigacion/tu-piel-como-interfaz-tactil-los-tatuajes-duoskin-de-chip-nfc-a-joyas-con-leds>.
29. CHALAYAN, Hussein, WRIGHT, Adam. One hundred and eleven [online], [accessed 20. 3. 2019]. Available on World Wide Web: <http://adam-wright.com/jobs/hussein-chalayan-one-hundred-eleven/>.
30. Studio XO. Volantis [online], [accessed 20. 3. 2019]. Available on World Wide Web: <https://the-dots.com/projects/volantis-by-studio-xo-138515>.
31. GAO, Ying. (No)where (now)here [online], [accessed 20. 3. 2019]. Available on World Wide Web: <https://design-milk.com/nowhere-nowhere-interactive-dresses-by-ying-gao/>.
32. WALDEMEYER, Moritz. Bono's laser jacket [online], [accessed 20. 3. 2019]. Available on World WideWeb:<https://www.dezeen.com/2010/02/28/bonos-laser-stage-suit-by-moritz-waldemeyer/>.
33. CuteCircuit. Twitter dress [online], [accessed 20. 3. 2019]. Available on World Wide Web: <http://cutecircuit.com/nicole-twitter-dress/>.
34. MODESTA, Viktoria. WIIPPRECHT, Anouk. Sonifica [online], [accessed 20. 3. 2019]. Available on World Wide Web: <https://www.pinterest.com/pin/316518680053369567/>.
35. CuteCircuit. Soundshirt [online], [accessed 20. 3. 2019]. Available on World Wide Web: <http://cutecircuit.com/soundshirt/>.
36. CuteCircuit. Soundshirt [online], [accessed 20. 3. 2019]. Available on World Wide Web: <http://www.lustermagazine.com/sound-shirt-sinfonia-alemana-wearable/>.
37. Cutecircuit. Hugshirt [online], [accessed 23. 3. 2019]. Available on World Wide Web: <https://crunchwear.com/cutecircuit-hug-shirt/>.
38. CO, Elise. Puddle jumper [online], [accessed 23. 3. 2019]. Available on World Wide Web: <https://www.electricfoxy.com/electricfoxy/ 2009/01/luminescent-raincoat>.
39. RILLE, Martin. Coded sensation [online], [accessed 23. 3. 2019]. Available on World Wide Web: <http://www.codedsensation.com>.
40. COLEMAN, Melissa, SMELT, Leonie, ROTTEVEEL, Joachim. The holy dress [online], [accessed 23. 3. 2019]. Available on World Wide Web: <http://melissacoleman.nl/holydress>.
41. JEON, Eunjeong. Trans-For-M-Otion [online], [accessed 23. 3. 2019]. Available on World Wide Web: <http://eunjeongjeon.wixsite.com/infor/projectpage-cv7b>.
42. WIPPRECHT, Anouk, SCHATZMAYR, Daniel. Robotic spider dress [online], [accessed 23. 3. 2019]. Available on World Wide Web: <https://fashioningtech.com/2013/01/07/robotic-couture/>.
43. FARAHI, Behnaz. Opale [online], [accessed 23. 3. 2019]. Available on World Wide Web: <http://behnazfarahi.com/opale/>.
44. WALDEMEYER, Moritz. Fashion projects [online], [accessed 25. 3. 2019]. Available on World Wide Web: <http://www.waldemeyer.com/category/fashion>.
45. WRIGHT, Adam. Hussein Chalayan / *Adam Wright* [online], [accessed 25. 3. 2019]. Available on World Wide Web: <http://adam-wright.com/tag/hussein-chalayan/>.
46. MILLER LANDAU, Deb. Hussein Chalayan brings biosensing to Paris Fashion Week [online], [accessed 25. 3. 2019]. Available on World Wide Web: <https://iq.intel.in/hussein-chalayan-brings-biosensing-wearables-to-paris-fashion-week/>.
47. WIPPRECHT, Anouk. Anouk Wipprecht Fashion Tech [online], [accessed 25. 3. 2019]. Available on World Wide Web: <http://www.anoukwipprecht.nl/bio>.
48. MCCHAREN, Becca. Chromat [online], [accessed 25. 3. 2019]. Available on World Wide Web: <https://chromat.co/pages/about-us>.
49. HARTMAN, Kate. OCAD University [online], [accessed 25. 3. 2019]. Available on World Wide Web: <https://www2.ocadu.ca/bio/kate-hartman-0>.
50. SEYMOUR, Sabine. Moondial [online], [accessed 25. 3. 2019]. Available on World Wide Web: <http://moondial.com/2010/seymour/>.
51. FRIED, Limor. Adafruit Industries. Unique & fun DIY electronics and kits [online], [accessed 25. 3. 2019]. Available on World Wide Web: <https://www.adafruit.com/about>.
52. PANTOUVAKI, Sofia. Embodied interactions: Towards an exploration of the expressive and narrative potential of performance costume through wearable technologies. *Scene,* 2014, **2**(1+2), 179–196, doi: 10.1386/scene.2.1-2.179_1.
53. KAPLAN, Ken. Future tech fashion styles hit NYFW runway [online], [accessed 20. 3. 2019]. Available on World Wide Web: <https://iq.intel.com/future-tech-fashion-styles-hit-nyfw-runway/>.
54. Manus x Machina - Metropolitan museum of art [online], [accessed 20. 3. 2019]. Available on World Wide Web: <https://www.metmuseum.org/exhibitions/listings/2016/manus-x-machina>

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Obnašanje potrošnikov pri kupovanju tekstila v Republiki Srbiji

Clothes Consumption in Republic of Serbia: Customer Behaviour Overview

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Izvleček

V članku je predstavljena raziskava potrošniških navad pri kupovanju oblačil v Republiki Srbiji. Cilj raziskave je bil odgovoriti na naslednja vprašanja: kje prebivalci najpogosteje kupujejo oblačila, kako pogosto hodijo po nakupih in koliko mesečno porabijo zanje ter kaj se jim pri kupovanju oblačil zdi najpomembnejše. V ta namen je bila s pomočjo spletnega vprašalnika s tehniko Computer Assisted Web Interviewing (CAWI) opravljena raziskava na vzorcu 500 vprašanih. Pokazalo se je, da okoli 40 odstotkov prebivalcev Republike Srbije kupi določen kos oblačil enkrat na mesec, 36 odstotkov pa jih kupi nekaj oblačil enkrat v treh do šestih mesecih. Oblačila najpogosteje kupujejo v trgovinah z blagovnimi znamkami (53 odstotkov), tretjina prebivalcev pa hodi večinoma v manjše, lokalne trgovine in butike, kjer so naprodaj kosi, ki nimajo uveljavljenih blagovnih znamk. Prebivalci najpogosteje kupujejo v kraju, kjer živijo, ali pa v neposredni okolici. Oblačila dokaj pogosto kupujejo tudi v drugih mestih v Srbiji (29 odstotkov) oziroma v tujini – predvsem v sosednjih državah (20 odstotkov), če je tam ponudba ugodnejša, ali zaradi nakupa modelov in blagovnih znamk, ki jih na domačem trgu ni. V povprečju skoraj 60 odstotkov prebivalcev Republike Srbije porabi za nakup oblačil do 40 evrov na mesec, s čimer se na letni ravni Republika Srbija primerja s sosednjimi državami, članicami EU (na primer s Hrvaško in Madžarsko). Poleg tega so bile v raziskavi opredeljene tri skupine potrošnikov (neodvisno od demografskih spremenljivk), podani pa so tudi drugi zanimivi sklepi, do katerih so raziskovalci prišli z analiziranjem izhodiščnih hipotez, ki bolje pojasnjujejo trg Republike Srbije.
Ključne besede: nakup, oblačila, blagovna znamka, trg

Abstract

This paper explores consumer habits in the Republic of Serbia regarding the purchase of clothes. The aim of the research was to answer the following questions: where do the citizens of Serbia buy clothes most often, how often do they go shopping, how much money do they spend monthly and what is most important for them when buying clothes? A survey was conducted among 500 respondents by means of an online questionnaire using Computer Assisted Web Interviewing (CAWI). The findings showed that about 40% of Serbian citizens buy clothing items once a month, while 36% of them buy once in 3–6 months. Clothes are most frequently purchased in branded shops (53%), while one third of citizens mainly go to smaller, local shops and boutiques with unbranded items. Citizens usually buy clothes in the city they live in or in the immediate surroundings. However, clothes are often bought in other cities of Serbia (29%) or abroad, most notably in the neighbouring countries (20%) if the offer is cheaper or for the purpose of purchasing the models and brands that are not available on the local market. On average, nearly 60% of Serbian citizens spend up to EUR 40 per month on the purchase of clothes, which puts them at the annual level on a par with the neighbouring countries that are EU members (i.e. Croatia and Hungary). The research also defined three different groups of consumers (independently of demographic variables). Moreover, other interesting conclusions were drawn by analysing the initial hypotheses of the paper that better explain the market in the Republic of Serbia.
Keywords: shopping, clothes, brand, market

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1 Uvod

Poslovno okolje se nenehno spreminja. Na makroravni globalizacija vpliva na ekonomsko okolje, na mikroravni se krepi konkurenca zaradi globalizacije trga, zahtevam potrošnikov pa je treba ugoditi [1]. V tem okviru je treba obravnavati tudi trg oblačil, ki je v zadnjih dvajsetih letih doživel velike spremembe, po podatkih Gospodarske zbornice Srbije se je na primer Blumbergov indeks tekstila od leta 2012 do konca leta 2016 opazno povečal, tako kot skupni svetovni izvoz oblačil in obutve.

V času globalizacije se podjetja odločajo delovati v mednarodnem okolju, ki prinaša priložnosti in izzive hkrati [2]. Globalizacija po eni strani odpira nov trg, po drugi pa je resen izziv v zvezi z marketinško strategijo. V zadnjih dveh desetletjih je internacionalizacija poslovanja v tekstilni in modni industriji postala eden odločilnih dejavnikov rasti podjetij v tej gospodarski panogi, ki se bojujejo med seboj in na najrazličnejše načine poskušajo najti pot do tujih trgov. Mehanizmi, ki jih podjetja izberejo za vstop, razvoj in distribucijo svojih blagovnih znamk, lahko temeljijo na klasičnem izvozu, franšizingu, skupnih vlaganjih z lokalnimi podjetji, licenčnih aranžmajih, ustanavljanju lastnih podružnic ipd. Izbor je odvisen od posebnosti lastnine podjetja in vrednosti blagovne znamke, finančne zmožnosti podjetja, mednarodnih izkušenj, nujnih za poslovanje na tujih trgih, ter lastnosti tuje države v smislu odnosa demografskega in nakupovalnega potenciala ter prednosti, ki jih kupci kažejo na lokalnem trgu in ki so predstavljene v tem prispevku.

Glede na to, da se trg čedalje bolj segmentira, se kot eno temeljnih načel trženja »podjetja skladno s prizadevanji za boljšo osredinjenost« [3] osredinijo na kupce, pri katerih je največ možnosti za zadovoljstvo [4]. Sektor modne maloprodaje v tem primeru omogoča relevanten kontekst, pri čemer je paradoksalni izziv za koncept segmentacije v širjenju heterogenosti, ki naj bi jo ta pristop presegel. Modni trg že po svoji naravi karakterizira nestabilno povpraševanje in to, da dejavniki, kot so starost, osebni dohodek, življenjski slog in kultura, vplivajo na specifičen fragmentiran tržni kontekst [5]. Hofstede [6] poudarja, da je »delo v vsaki državi drugačna igra z različnimi pravili«. Ta »pravila« so po Hofstedu in drugih avtorjih [6–8] tesno povezana z lokalno kulturo.

Potrošniki sodobnih modnih oblačil so predvsem dobro informirani in zahtevnejši pri svojih pričakovanjih. Ni več naloga mode zadovoljiti estetsko komponento, temveč morajo biti modni izdelki kakovostni, lepi, praktični, morajo odražati osebnost kupca, njegov poklic in način življenja, njegovo filozofijo [9].

Odločitev o nakupu oblačil je prej temeljila na realnih potrebah potrošnikov in razpoložljivih finančnih sredstvih [10], v novem tisočletju pa je namen nakupa obleke (z blagovno znamko) pogosto ustvariti poseben videz oz. izbrati želeno identiteto v simboličnih vrednostih, s čimer se zadovoljijo potrebe, ki niso v neposredni zvezi z nakupom oblačil [11]. "Ljudje pogosto sami sebe opredelijo glede na to, kaj imajo" [12]. Poleg tega je nakupovanje pomemben vidik vsakdanjega življenja. Obisk trgovskih centrov in trgovin je za mnoge postal več kot nujna obveznost, gre za dodatno dejavnost za prosti čas in druženje. Zato neko modno podjetje ne more uspeti brez podrobnih informacij o trgu, na katerem nastopa, ne samo v smislu njegovih trenutnih potreb, temveč tudi v smislu napovedi tržnih gibanj na srednjeročni, če je mogoče, pa tudi na dolgoročni ravni. V prispevku bodo le-ti predstavljeni skozi analizo sedanjega položaja in napovedi za naprej.

Na porabo v segmentu FMCG (Fast Moving Consumer Goods – blago za široko porabo) vpliva več različnih dejavnikov, kot so: splošen gospodarski in finančni položaj države, položaj v gospodarski panogi, struktura in finančna moč potrošnikov, sociološki in kulturološki vplivi na porabo itd. V tem pogledu je Republika Srbija v posttranzicijskem obdobju, za katerega sta značilna nezadosten splošen gospodarski razvoj in nestabilno finančno okolje. Da pa Srbiji le gre na boljše, kažejo naslednji podatki iz leta 2018. Kot kažejo viri Narodne banke Srbije [13] in poročilo Republiškega zavoda za statistiko [14], ima Srbija 3,8-odstotno rast BDP. V poročilu Narodne banke Srbije je navedeno, da sta k rasti BDP pripomogli rast investicij in porabe in rast izvoza. Investicije rastejo, čeprav je poročilo Svetovnega ekonomskega foruma [15] Srbijo uvršča na visoko drugo mesto med državami s tveganimi naložbami v letu 2017, saj je Srbija dosegla največ naložb od leta 2010 naprej.

H1: Čeprav je uradno povprečni neto zaslužek v RS (po podatkih Zavoda za statistiko Republike Srbije okoli 460 evrov) [16] bistveno manjši kot v okoliških državah, ki so članice EU, povprečen prebivalec RS za tekstil in oblačila porabi znatno vsoto glede na povprečni dohodek.

»Trenutni trendi v razvoju maloprodaje, ki so posledica globalizacije, zahtevajo redistribucijo potrošniškega proračuna z visokomarginalne offline potrošniške košarice na nizko maržo spletne potrošniške košarice, ki spodbuja ne samo potrebo po transformacijah v menedžmentu, temveč tudi študije obnašanja potrošnikov« [17]. Kupci se čedalje pogosteje odločajo za spletne nakupe in ljudje čedalje pogosteje naročajo izdelke po spletu. To potrošnikom omogoča preprosto izbiro želenega izdelka in dostavo na domači naslov v sorazmerno kratkem času, kar je značilno za nakupe, za katere se radi odločajo mladi kupci. Ženske so bolj nagnjene k sledenju modnim novostim in modnim smernicam [18], zato pričakujemo, da ženske pogosteje kot moški pokažejo večje zanimanje za obleko in so bolj nagnjene k modni ozaveščenosti [19, 20]. Poleg tega so ženske bolj naklonjene stereotipom v zvezi z modnimi izdelki [21]. Mlajši potrošniki so pod večjim vplivom mode [22]. Radi preskušajo nove izdelke in so naklonjeni znanim blagovnim znamkam ter so manj občutljivi pri ceni [23]. Ravno tako mladi na splošni ravni več uporabljajo splet kot pa starejši potrošniki, kar se pozna pri številu nakupov po spletu [24]. Na podlagi prejšnjih raziskav predlagamo naslednjo hipotezo:
H2: Ženske in mladi v RS so bolj pozorni na oblačila z blagovnimi znamkami in jih kupujejo več kot druge skupine.
»Najuspešnejše blagovne znamke bodo na ustrezen način predstavile generacijsko potrebo po individualnosti, pa tudi čas in dogodke v družbi. Toda, ko vsaka generacija doseže določena leta, so potrebe zelo podobne, kar vodi k različnemu oglaševanju za vsako generacijo, toda s podobnimi izdelki« [25]. Na splošno so pričakovanja od nakupa in blagovnih znamk pri starejših in mlajših kupcih različna. Starejši potrošniki se manj zavedajo novosti, saj kažejo več rutinskega obnašanja, imajo raje stalne blagovne znamke in so manj pripravljeni preizkušati nove izdelke [26]. Starejši potrošniki so tudi manj naklonjeni k iskanju novih informacij [27]. Starejši, samozavestni potrošniki, v nasprotju z mladimi drugače razumejo nakup oblačil. Ne želijo se odpovedati dobrim oblačilom in drugim modnim detajlom, od katerih pričakujejo funkcionalnost, praktičnost, primernost za lasten življenjski slog. [28]. Na tej podlagi je nastala tretja hipoteza:
H3: Starejši potrošniki v Republiki Srbiji redkeje kupujejo oblačila z blagovnimi znamkami po spletu.

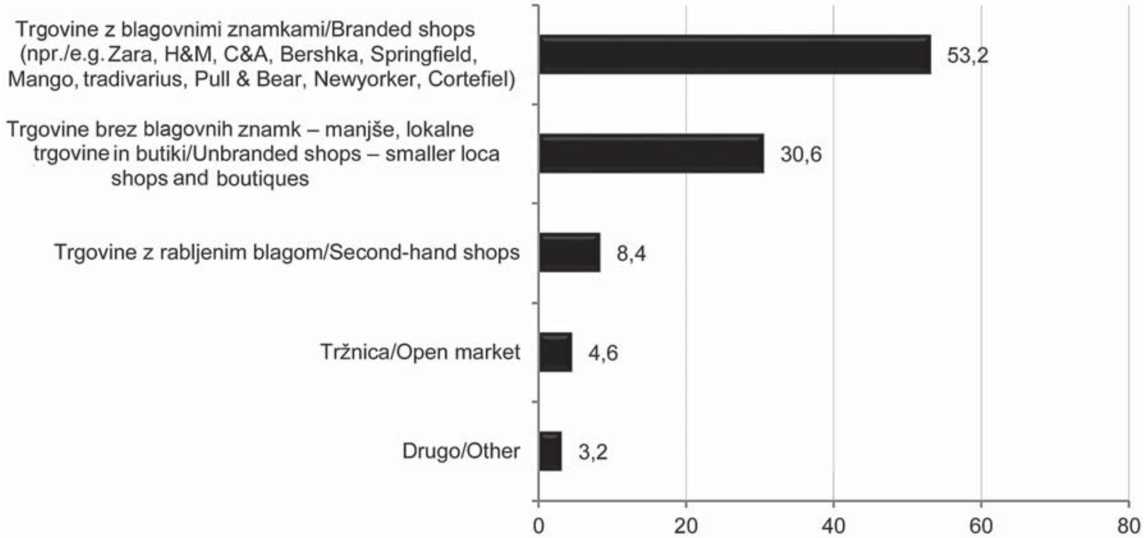
2 Metode

Raziskava je bila izvedena v septembru 2018 in glede na izkazano potrebo so avtorji sodelovali z Gospodarsko zbornico Srbije (v prejšnjih tridesetih letih v Srbiji ni bilo podobnih raziskav). Cilj raziskave je bil dobiti odgovore na več vprašanj, med katerimi navajamo najpomembnejša:
Kje prebivalci Srbije najpogosteje kupujejo oblačila? Kako pogosto gredo po nakupih? Koliko na mesec za to porabijo in kaj je zanje pri kupovanju garderobe najpomembnejše? Cilj raziskave je bil tudi definirati skupine potrošnikov glede na njihove želje in navade, ne glede na demografske spremenljivke, ki jih povezujejo ali ločujejo.
Raziskava je bila po svoji naravi kvantitativna in je bila izpeljana skozi strukturirani vprašalnik, kot instrument za zbiranje primarnih podatkov v raziskavi, ki so zajemali vprašanja v zvezi s sociodemografskimi podatki o izpraševancu, skupino vprašanj, ki so hkrati pomenila odvisne spremenljivke. Anketirani so bili samo polnoletni prebivalci, razdeljeni v tri starostne kategorije: mladi (18–34 let) ‑ 208 vprašanih, srednjih let (35–54 let) ‑ 241 vprašanih, ter starejši (55 let in več) ‑ 51 vprašanih, razmerje med ženskami in moškimi pa je bilo 266 proti 234, medtem ko je geografska spremenljivka pomenila naseljenost štirih regij: Beograd, severna Srbija ‑ Vojvodina, jugovzhodna Srbija in osrednja ter zahodna Srbija. Anketo so opravili strokovnjaki s pomočjo CATI-tehnike (Computer Assissted Telephone Interviewing). Med drugim so vprašani na sedemstopenjski lestvici Likertovega tipa ocenjevali, koliko je pri nakupu garderobe zanje pomemben vsak od naslednjih vidikov: cena, kakovost, blagovna znamka, dizajn in praktičnost (udobnost, značilnosti blaga ipd.).
Da bi dobili podrobnejši vpogled v identificirane skupine potrošnikov, so bile testirane razlike med tremi skupinami vprašanih pri njihovih sociodemografskih značilnostih, potrošniškem obnašanju, nakupovalnih navadah in spletnih nakupih. Pokazale so se razlike na ravni spola, osebnih dohodkov in stopnje naložb v nakup oblačil skupaj s spletnimi nakupi.
Nazadnje je bila opravljena analiza korespondence, da bi oblikovali integrirano vizualno podobo potrošniških skupin. V analizo so bile vključene vse spremenljivke, ki so pomembno ločile tri skupine

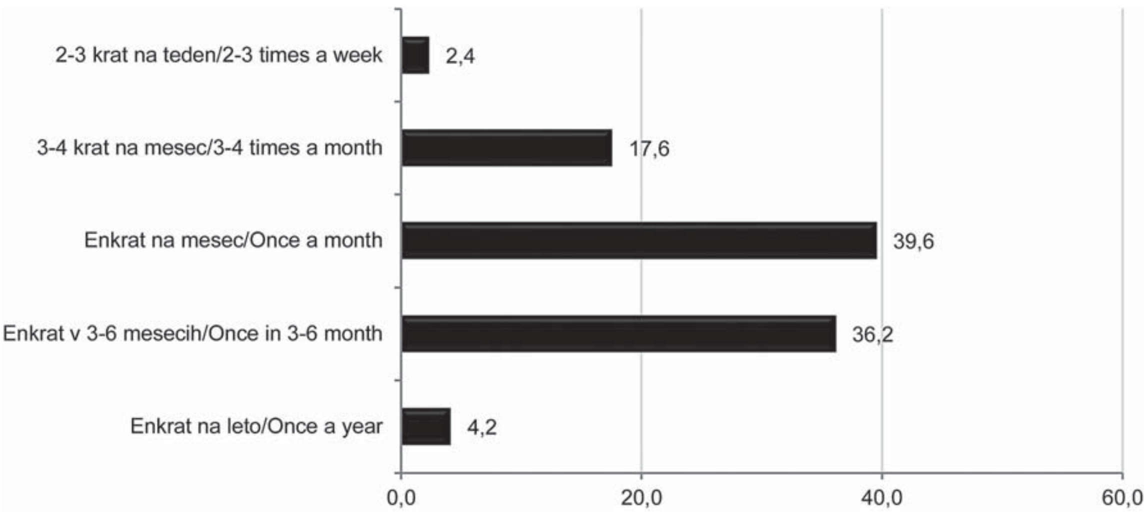
vprašanih. Pri spremenljivkah, ki so numerične (sedemstopenjska lestvica Likertovega tipa), je bila takole opravljena transformacija v kategorične spremenljivke: seštevki za vsako numerično spremenljivko so bili izračunani kot seštevek vprašanih, ki so pri določeni spremenljivki dali največ dve oceni (6 in 7). Glede na to, da so se raziskane numerične spremenljivke nanašale samo na oceno pomembnosti različnih vidikov nakupa, so bili tako izbrani anketiranci, ki menijo, da je določen vidik nakupa pomemben ali zelo pomemben.

3 Rezultati in razprava

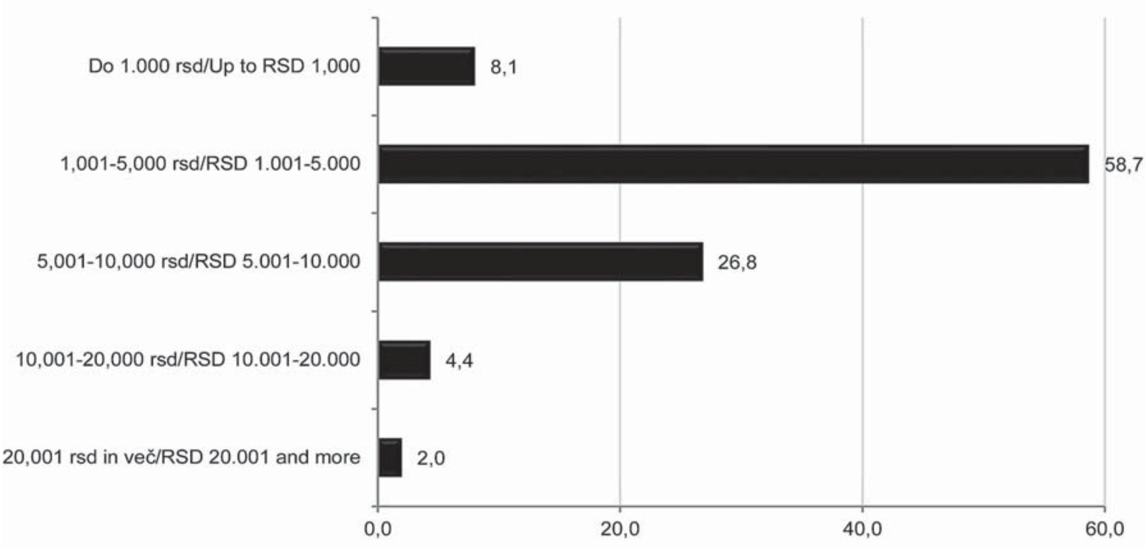
Raziskava je pokazala, da nekaj več kot polovica prebivalcev Srbije najpogosteje kupuje v blagovnih trgovinah z blagovnimi znamkami (53,2 %), tretjina pa kupuje v manjših lokalnih trgovinah in butikih, ki ne ponujajo izdelkov z blagovnimi znamkami. Skupaj okoli 16 % prebivalcev daleč največ kupuje v trgovinah z rabljenim blagom, na tržnicah in na drugih mestih, kot je razvidno iz slike 1. S stališča modne industrije je to glede na povprečno kupno moč prebivalcev kar soliden rezultat.



Slika 1: Pregled odgovorov na vprašanje, kjer ljudje najpogosteje kupujejo
Figure 1: Answer distribution to question where the purchase is made most commonly



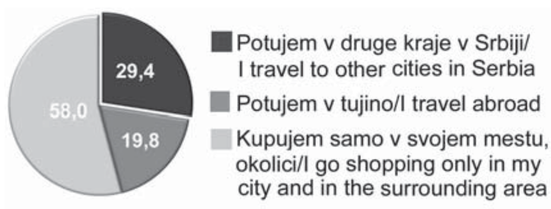
Slika 2: Porazdelitev odgovorov glede na pogostnost nakupov
Figure 2: Distribution of answers regarding purchase frequency



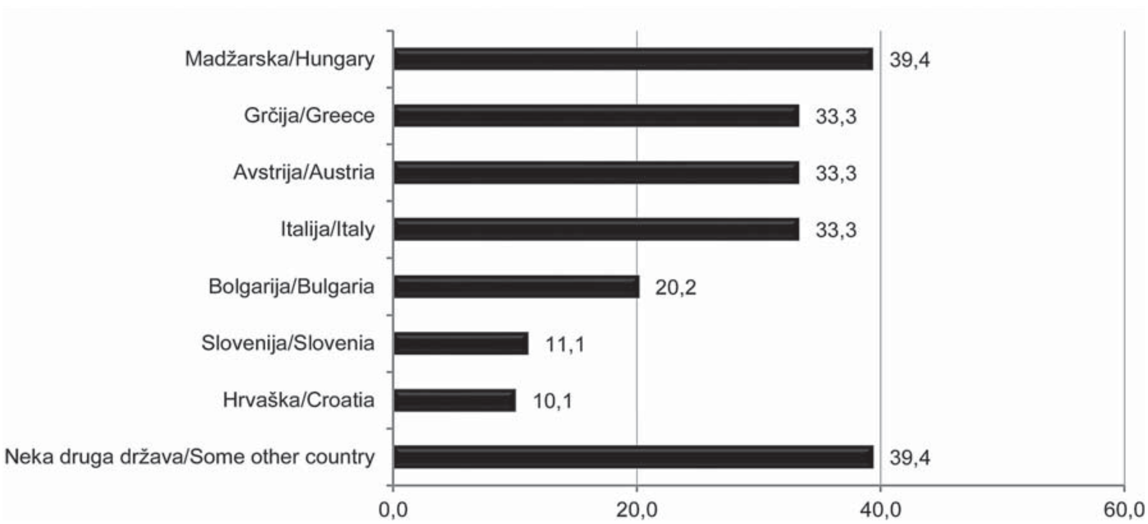
Slika 3: Porazdelitev odgovorov glede na mesečno porabo
Figure 3: Distribution of answers regarding monthly consumption

Ni pa tako obetavna frekvenca nakupov: manj kot petina prebivalcev (17,6 %) kupuje večkrat na mesec, največ pa jih kupuje enkrat na mesec (39,6 %) ali na tri do šest mesecev (36,3 %). Slika 2 daje natančen vpogled v vse definirane kategorije kupcev oblačil v Republiki Srbiji. Vendar domnevamo, da ta prevladujoči del vzorca, tri četrtine (39,6 in 36,3 %) opravi večje nakupe takrat, ko so v trgovinah večji popusti, kar bodo avtorji ugotavljali v prihodnji raziskavi.
Zanimivi so rezultati, povezani z mesečno porabo: večina potrošnikov v Srbiji porabi do 42,50 evra – 58,7 %, več kot četrtina (26,8 %) porabi od 42,50 evra do 85 evrov na mesec (26,8 %), kar kaže slika 3 zgoraj.

Slika 4 kaže preference prebivalcev Srbije pri kupovanju oblačil v tujini.



Slika 4: Porazdelitev odgovorov glede na kraj nakupa
Figure 4: Distribution of answers regarding purchase location



Slika 5: Razdelitev odgovorov glede na države, v katerih kupujejo
Figure 5: Distribution of answers regarding countries where clothes are purchased

Ob tem je petina vprašanih, ki oblačila kupujejo v tujini, navedla bližnje države, med katerimi izstopajo tiste, ki so navedene na sliki 5.

Da bi ugotovili, ali je mogoče izločiti skupine potrošnikov glede na vidike nakupov, katerim pripisujejo večji pomen, je bila izvedena hierarhična analiza skupin. Na podlagi dendograma je bila izbrana rešitev s tremi skupinami, ki se med seboj najbolj razlikujejo na podlagi pomembnosti omenjenih vidikov nakupa. Multivariacijska analiza variance je potrdila, da se tri skupine potrošnikov bistveno razlikujejo v vseh vidikih nakupa ($V = 1,09$ $F(10, 988) = 119,9$, $p = 0,00$).

Na sliki 6 so povprečne vrednosti treh skupin vprašanih predstavljene skozi Likertonovo lestvico (z odgovori, navedenimi na lestvici 1-7, kjer 1 pomeni najmanjše soglašanje s trditvijo, 7 pa največje).

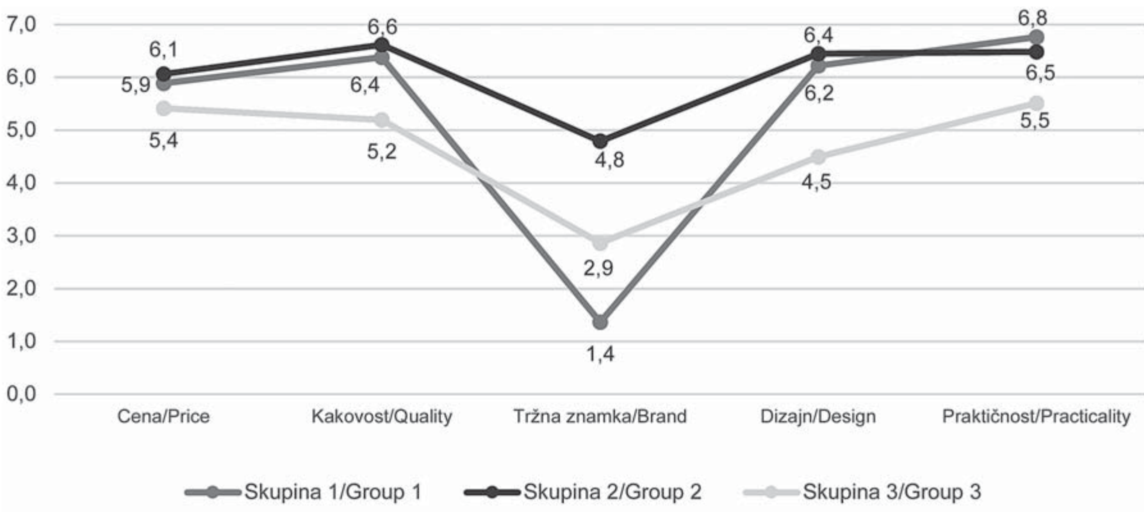
Za prvo skupino vprašanih imajo blagovne znamke opazno najmanjši pomen: M (sredina) = 1,4, SE (statistična napaka) = 0,10) in gre za vidik, kjer se tri skupine najbolj razlikujejo. Skoraj vsi pripadniki prve skupine navajajo, da je zanje praktičnost izjemno pomembna (M = 6,8, SE = 0,08), čeprav se jim zdijo zelo pomembni tudi drugi vidiki nakupa. Po drugi strani druga skupina potrošnikov izstopa s tem, da so zanje blagovne znamke najpomembnejše (M = 4,8, SE= 0,07), čeprav je sama blagovna znamka v primerjavi z drugimi vidiki najmanj pomembna za potrošnike ne glede na skupino, v katero spadajo. V drugi skupini vprašanih so vsi vidiki nakupa zelo pomembni, v tretji pa so težnje nasprotne. Z izjemo blagovne znamke so vsi drugi vidiki najniže ocenjeni, če to primerjamo s prvo in drugo skupino vprašanih.

Na sliki 7 je predstavljena analiza korespondence za tri skupine vprašanih, katerim so v tej fazi dana imena.

Na podlagi navedenih analiz je v nadaljevanju predstavljen opis vsake od treh identificiranih skupin vprašanih.

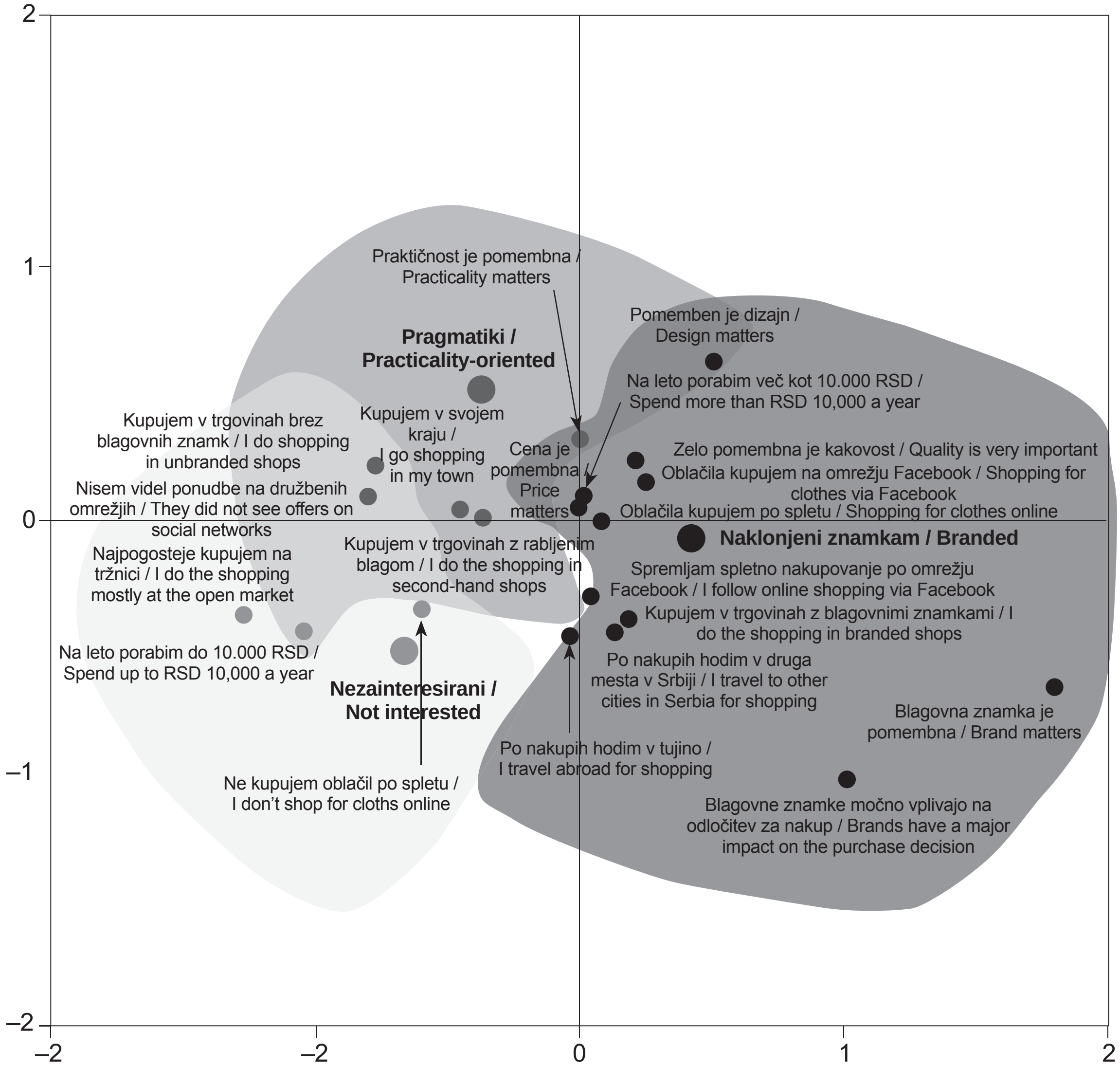
Pragmatiki

To je prva skupina vprašanih, za katere so blagovne znamke najmanj pomembne. Poleg tega je za te potrošnike ob nakupu najpomembnejša praktičnost, oziroma udobnost, značilnosti blaga in podobno. V skladu s pragmatičnostjo in na splošno majhno zainteresiranostjo za oblačila blagovnih znamk je ta skupina vprašanih nagnjena h kupovanju v trgovinah brez blagovnih znamk ali trgovinah z rabljenimi oblačili. Poleg tega nakupovalni turizem ni tako značilen za praktične, ti oblačila pogosteje kupujejo v svojem kraju in okolici. Drugi vidiki ob nakupu, kot so dizajn, kakovost in cena, so zanje tudi pomembni, toda ne toliko kot praktičnost. Zanimivo je, da se v tej skupini potrošnikov pogosteje najdejo ženske kot moški. To so zelo skrbni potrošniki, ki ob nakupu upoštevajo vse vidike in si prizadevajo, da bi po ugodni ceni dobili čim boljša in kakovostna oblačila. Več kot pol vzorca je žensk (62 %), starih od 35 do 54 let (53 %). Druga najštevilnejša skupina so osebe, stare od 18 do 34 let (39 %). Enako je zastopan ta segment v vseh krajih, več kot pol pa je



Slika 6: Povprečna vrednost treh skupin vprašanih na podlagi pomembnosti različnih vidikov nakupa na Likertonovi lestvici (vrednosti 1–7)

Figure 6: Average value of three clusters of respondents based on importance of various purchase aspects on a Likert scale (1–7)



Slika 7: Razsevni diagram preproste korespondenčne analize – prikaz profilov treh skupin anketirancev
Figure 7: Random diagram of simple correspondence analysis – View of profiles of three groups of respondents

stalno zaposlenih (61 %) in z višjo izobrazbo (65 %) ter imajo povprečno kupno moč.

Nakupi po spletu pri praktikih še vedno ne prevladujejo, čeprav uporabljajo družbena omrežja. Polovica jih je kdaj kupila kakšno oblačilo po Facebooku, preostali pa ponudbe na družbenih omrežjih ne spremljajo ali pa je niti niso videli.

Naklonjeni blagovnim znamkam

Naklonjeni blagovnim znamkam so potrošniki, za katere so nakupi sestavni del življenjskega sloga in jih opravljajo po različnih kanalih komunikacije ter na različnih prodajnih mestih. Osrednja značilnost te skupine je, da cenijo tiste blagovne znamke, ki lahko pomembno vplivajo nanje ob nakupu oblačil, in prav ti najpogosteje obiskujejo trgovine z blagovnimi znamkami. Za to skupino potrošnikov so pomembni vsi vidiki nakupa, vendar so poleg blagovnih znamk še zlasti pozorni na kakovost oblačil. Zanimivo je, da je med ljubitelji blagovnih znamk približno enako število moških in žensk. Poleg tega je to skupina potrošnikov, ki ima najpogosteje večjo kupno moč in v povprečju za nakup obleke porabi več denarja kot drugi potrošniki. Glede na pozornost, ki jo kupci, naklonjeni blagovnim znamkam, namenjajo nakupu in oblačilom z blagovnim znamkami, lahko domnevamo, da se v tej skupini najdejo tudi »impulzivni potrošniki«.

Pogosto se zdi, da je veliko ljudi, ki kot kupci čutijo potrebo, da so nekaj posebnega [9]. Kupci, naklonjeni blagovnim znamkam, so privrženi tudi nakupovalnemu turizmu in zato najpogosteje zaradi nakupa oblačil obiskujejo druge kraje v Srbiji, ali pa gredo kupovat celo v tujino. Pričakovano so kupci, naklonjeni blagovnim znamkam, v največjem številu izjavili, da kupujejo po spletu, in sicer predvsem po Facebooku, ko gre za nakup na družbenih omrežjih.

V tej skupini je enaka zastopanost moških in žensk, pol potrošnikov je starih od 35 do 54 let (48 %). Enaka je tudi zastopanost ljubiteljev tržnih znamk v vseh regijah. Pri socioekonomskem statusu gre najpogosteje za povprečno raven (31 %) ali raven, ki je malo nad povprečjem – 33 %. Največ ljubiteljev blagovnih znamk je stalno zaposlenih (56 %), z visoko (63 %) ali srednjo izobrazbo (32 %).

Nezainteresirani

To so pogosteje pripadniki moškega spola z načeloma nižjimi osebnimi dohodki glede na potrošnike, ki imajo raje oblačila z blagovnimi znamkami. Kot pove že samo ime, le-ti kažejo najmanjšo zainteresiranost za nakup oblačil in povprečno porabijo do 85 evrov na leto. V skladu s slabo zainteresiranostjo za nakupovanje se jim skoraj vsi vidiki nakupa zdijo manj pomembni kot ljubiteljem blagovnih znamk in potrošnikom, usmerjenim v praktičnost. Če pa primerjamo ocenjevanje različnih vidikov nakupa, sta za nezainteresirane potrošnike cena in praktičnost najpomembnejša.

Blagovne znamke in trgovine z blagovnimi znamkami imajo za to skupino potrošnikov opazno manjši pomen, saj pogosteje kupujejo v trgovinah brez blagovnih znamk in na tržnici. Nezainteresirani potrošniki so tudi najbolj oddaljeni od spletnega nakupa in glede na drugi dve skupini vprašanih najpogosteje niso kupovali po spletu in niso opazili ponudb na družbenih omrežjih.

V tem segmentu potrošnikov je nekaj več moških (58 %) kot žensk (42 %), starih od 18 do 34 let (46 %) in od 35 do 54 let (42 %). V glavnem imajo povprečne dohodke, tako kot praktični potrošniki (38 %). Polovico skupine tvorijo stalno zaposleni (51 %) z visoko (56 %) ali srednjo izobrazbo (38 %). Kar polovica nezainteresiranih milenijcev prihaja iz Beograda.

Na podlagi navedenega in analize korespondence lahko sklepamo, da imajo nezainteresirani uporabniki skupne značilnosti s prvo skupino potrošnikov glede pomembnosti, ki velja za pragmatičnost, pa tudi nagnjenosti h kupovanju v trgovinah brez blagovnih znamk, na tržnicah in sploh glede na to, da porabijo manj denarja kot ljubitelji blagovnih znamk. Razlika med obema skupinama vprašanih je v dejstvu, da ti potrošniki načeloma niso zainteresirani za nakupe in jim ne pripisujejo tolikšnega pomena kot praktični potrošniki.

Analiza vseh treh skupin kaže, da povprečna izobrazba ne vpliva na uvrščenost v skupino ter da je pri nakupu oblačil z blagovnimi znamkami izražen ekonomski status.

3.1 Nakupi po svetovnem spletu

Po Eurostatu so se v EU-28 v letu 2017 po spletu najpogosteje kupovala oblačila in športno blago (64 %), turistične in praznične namestitve (53 %), gospodinjski pripomočki (46 %), vstopnice za dogodke (39 %) ter knjige, revije in časopisi (34 %). Od petih e-kupcev je manj kot eden kupil telekomunikacijske storitve (19 %), računalniško opremo (18 %), zdravila (13 %) in učno gradivo (6 %).

Po raziskavah [29] je v Srbiji nekaj več kot pol uporabnikov spleta (57 %) imelo izkušnje z nakupom oblačil po spletu. Med spletnimi kupci večinoma vsak drugi naroči oblačila prek domačih spletnih strani, okoli 15 % pa jih ima raje tuje spletne strani. Glavni trije razlogi, zaradi katerih srbski spletni uporabniki raje kupujejo prek tujih spletnih strani, so: te ponujajo izdelke, ki jih ni mogoče kupiti v Srbiji, ali pa več izdelkov in storitev in ugodnejše cene. Pri lokalnih spletnih straneh je velika večina srbskih spletnih kupcev (75 %) bolj zainteresirana za kupovanje na spletnih straneh Limundo, Kupindo, Kupujem-Prodajem itn. Ti kupujejo oblačila, obutev in športno opremo. Med najpogostejšimi razlogi tistih, ki ne kupujejo po spletu, je strah, da bodo dobili napačen izdelek, a raziskave kažejo, da je bila velika večina vprašanih v obeh letih zelo zadovoljna z nakupom na spletu, več kot 90 % uporabnikov ni imelo težav s spletnimi nakupi. Samo 15 % vprašanih v letu 2016 in 18 % v letu 2018 je izkoristilo možnost za pritožbo ali zamenjavo izdelka.

Udeleženost po starostnih skupinah je predstavljena v preglednici 1.

Kot vidimo, samo 10 % potrošnikov od tistih, ki so kupovali po spletu, spada v tretjo starostno skupino (stari 55 let ali več). Generacija Y je prva generacija, ki je zrasla na valu uvajanja in uporabe digitalne tehnologije in komunikacij. Dejstvo je, da je treba

Preglednica 1: Udeleženost po starostnih skupinah
Table 1: Collaboration by age groups

Ste kupovali oblačila na spletu?/*Have you bought clothes online?*	Obkrožite starostno kategorijo/*Age category*							
	18–34		35–54		55 in več/*55 and more*		Skupaj/*Total*	
	Št./*Count*	[%]	Št./*Count*	[%]	Št./*Count*	[%]	Št./*Count*	[%]
Da/*Yes*	122	58.7	144	59.8	20	39.2	286	57.2
Ne/*No*	86	41.3	97	40.2	31	60.8	214	42.8
Skupaj/*Total*	208	100.0	241	100.0	51	100.0	500	100.0

razumeti, kdo so milenijci in zakaj mislijo in delujejo drugače kot starejša generacija, ko gre za komunikacijo, obnašanje pri nakupih in odločanje. Razvoj industrijske tehnologije vodi v hitrejši razvoj generacij, vsaka generacija pa kaže posebnosti svojega obdobja. [30].

Prednostni način plačevanja je bilo za štiri od petih spletnih kupcev v Srbiji plačevanje z gotovino, le vsak peti kupec pa je plačeval s plačilnimi karticami – spletni kupci se raje odločijo za plačevanje z gotovino, ker so prepričani, da je to najvarnejši način plačevanja, plačilne kartice pa imajo za najlažji in najhitrejši način plačevanja [29].

Zaradi pomanjkanja denarja ali različnih načinov in navad potrošnikov je v zadnjih letih opazen trend odpiranja čedalje večjega števila trgovin z rabljenim blagom. Vsaka četrta oseba pravi, da vsaj tu in tam kaj kupi v tovrstnih trgovinah, podobno pogosto pa je kupovanje oblačil, ki se prodajajo na tržnicah. Vendar je prebivalcev, ki si tako kupujejo oblačila, verjetno še več.

Omejitve pri raziskavi

Spletno testiranje ima kot način zbiranja primarnih podatkov, pri katerem sodelujoči sami odločajo, ali bodo sodelovali ali ne, ne glede na solidno ugotovljeno reprezentativnost vzorca tudi vrsto omejitev. Čeprav so te omejitve precejšnje, menimo, da se zaradi števila vprašanih pridobljeni rezultati lahko obravnavajo kot zelo indikativni za dobljene sklepe. Optimalna raziskava bi morala biti kombinacija kvantitativnih in kvalitativnih raziskovalnih metod z zavestjo o zoperstavljanju različnim predsodkom, namesto da se domnevno raziskuje brez pristranskosti. Zato nameravajo avtorji to raziskavo ponoviti ter dodati kvalitativne metode, kot so fokusne skupine in globinski intervjuji s predstavniki interesnih skupin v tekstilni industriji.

4 Sklep

Če na podlagi dostopnih podatkov primerjamo, koliko povprečno prebivalec Srbije letno porabi za oblačila, je podobna poraba na Hrvaškem [31] in Madžarskem, čeprav je povprečni zaslužek v omenjenih dveh državah v povprečju enkrat višji. S tem se v celoti potrjuje prva hipoteza, ki hkrati dokazuje dobro poslovno vzdušje za tuje izvoznike ne glede na uradno relativno nizke dohodke. V tem pogledu prispevek daje tudi podatke o potencialu, ki jih vidijo tuji investitorji v obliki tekstilnih industrij in v državah v okolici, ki so velike proizvajalke oblačil (Italija, Avstrija, Romunija), kajti 95 % tekstilnega blaga je v Srbiji uvoženega [10], in potrjuje možnosti srbskega trga oblačil, ko gre za uvoz. Po podatkih Gospodarske zbornice Srbije iz leta 2017, za obdobje petih let, je uvoz tekstila, oblačil, usnja in obutve od leta 2012 (691 milijonov evrov) do leta 2016 strmo naraščal po približno 10-odstotni stopnji, na 1041 milijonov evrov.

Hipoteza 2 je samo delno potrjena, in sicer za mlade, kar je presenetljivo, rezultati pa kažejo, da starejši enako cenijo blagovne znamke (toda zagotovo bolj tiste, ki so vtisnjene v njihovo zavest, kot dolgotrajna potrošniška izkušnja), saj ženske pomenijo 62 % segmenta praktičnih potrošnikov – tistih, ki se nič kaj dosti ne ozirajo na blagovne znamke, temveč dajejo prednost udobnosti oblačil in lastnostim blaga. Potrditev dela hipoteze se ujema z raziskavo, ki jo je izvedla Ostojićeva in po kateri se mlajšim potrošnikom (19–35 let) zdi najpomembnejši prestiž, in to, da je blagovna znamka ime, ki je znano

širokemu krogu ljudi, ter da se s sprejemanjem mode želijo postaviti v družbi [10, 31]. S tem je zanikan prvi del tretje hipoteze, drugi pa je dokazan z izjemno majhnim deležem starejših potrošnikov pri spletnih nakupih (10 %).
V prihodnjih raziskavah na tem področju bi lahko obravnavali dodajanje drugih relevantnih marketinških spremenljivk, ravno tako pa bi bilo zaželeno opraviti podrobno primerjavo z državami v regiji, ki imajo podobno demografijo. Poleg tega naj bi investitorji na tem področju v zvezi z globljim vpogledom razmislili o skladnosti lastnih proizvodnih programov in imidžu blagovnih znamk v povezavi s prevladujočimi blagovnimi razmerami na trgih, na katere nameravajo vstopati ali na katerih nameravajo povečati naložbe, saj se je delitev evropskega trga na skupine držav izkazala kot pragmatičen način obravnavanja razlik in podobnosti [32].

Viri

1. TUDOR, Liviu. Change in textile and clothing industry. *Industria Textila,* 2018, **69**(1), 37–43.
2. HUDEA, Oana Simona, PAPUC, Răzvan-Mihail. International marketing strategies in the globalization era. *Lex et Scientia,* 2009, **16**(2), 301–311.
3. KOTLER, Pilip, ARMSTRONG, Gary. *Marketing: An introduction (2nd ed.)*. Englewood Cliffs : Prentice Hall, 1997.
4. DIBB, Sally. Market segmentation: strategies for success. *Marketing Intelligence and Planning,* 1998, **16**(7), 394–406, doi: 10.1108/02634509810244390.
5. HINES, Tony. Globalisation: An introduction to fashion markets and fashion marketing. In T. *Fashion marketing: Contemporary issues*. Uredila Tony Hines in Margaret Bruce. Oxford : Butterworth-Heinemann, 2001, pp. 1–25.
6. HOFSTEDE, Geert. *Culture's consequences: International differences in work-related values*. Volume 5, Cross-cultural research and methodologx series. Newbury Park, London, New Delhi : Sage Publications, 1980.
7. ZHANG, Yong, GELB, Betsy D. Matching advertising appeals to culture: The influence of products' use conditions. *Journal of Advertising*, 1996, **25**(3), 29–46.
8. VALAEI, Naser, RAZAEI, Sajad, KHAIRUZZAMAN WAN ISMAIL, Wan, MOI OH, Yoke. The effect of culture on attitude towards online advertising and online brands: applying Hofstede's cultural factors to internet marketing. *International Journal of Internet Marketing and Advertising*, 2016, **10**(4), 270–301.
9. SLIJEPČEVIĆ, Milica. *Modni marketing.* Beograd : HERAedu, 2016 pp. 286.
10. OSTOJIĆ, I. Percepcija modnih brendova od strane potrošača u Srbiji, *Marketing,* 2012, **43**(2), 157–168.
11. EVANS, Martin. Consumer behaviour towards fashion. *European Journal of Marketing,* 2013, **23**(7), 7–16, doi: 10.1108/EUM0000000000575.
12. O'CASS, Aron. Fashion clothing consumption: antecedents and consequences of fashion clothing involvement. *European Journal of Marketing,* 2004, **38**(7), 869–882, doi: 10.1108/03090560410539294.
13. *National Bank of Serbia. Macroeconomic developments in Serbia* [online], May 2019 [accessed 10. 1. 2019]. Available on World Wide Web: <https://www.nbs.rs/internet/english/18/18_3/presentation_invest.pdf>.
14. Quarterly gross domestic product in the Republic of Serbia – 3rd Quarter 2018 [online]. *Statistical release NR 40*, number 329 – year LXVIII, 30/11/2018. Statistical office of the Republic of Serbia [accessed 10. 1. 2019]. Available on World Wide Web: <http://publikacije.stat.gov.rs/G2018/pdfE/G20181329.pdf>.
15. *World Economic Forum. Inside report. Regional risks doing business 2018* [online], [accessed 18. 1. 2019]. Available on World Wide Web: <http://www3.weforum.org/docs/WEF_Regional_Risks_Doing_Business_report_2018.pdf>.
16. Zarade [online]. *Republika Srbija. Republički zavod za statistiku* [accessed 10. 4. 2019]. Available on World Wide Web: <http://www.stat.gov.rs/sr-latn/oblasti/trziste-rada/zarade/>.
17. DEPUTATOVA, Y. Yu., PSHENITSYNA, P. I., ILYASHENKO, S. B., BASKAKOV, V. A., ZVEREVA, A. O. Consumer behavior in the context of global economic transformations. *European Research Studies Journal*, 2018, **21**(2), 95–109.
18. MITCHELL, Vincent-Wayne, WALSH, Gianfranco. Gender differences in German consumer decision-making styles. *Journal of Consumer Behaviour*, 2004, **3**(4), 331–346.

19. KWON, Yoon-Hee. Sex, sex-role, facial attractiveness, social self-esteem and interest in clothing. *Perceptual and Motor Skills*, 1997, **84**(3), 899–907, doi: 10.2466/pms.1997.84.3.899.
20. PARKER, R. Stephen, HERMANS, Charles M., SCHAEFER, Allen D. Fashion consciousness of Chinese, Japanese and American teenagers. *Journal of Fashion Marketing and Management,* 2004, **8**(2), 176–186, doi: 10.1108/13612020410537870.
21. HOYER, Wayne D., MacINNIS, Deborah J. *Consumer behavior,* 5th edition. Boston ; New York : Houghton Mifflin, 2008.
22. WAN, Fang, YUON, Seounmi, FANG, Tammy. Passionate surfers in image-driven consumer culture: fashion-conscious, appearance-savvy people and their way of life. *Advances in Consumer Research*, 2001, **28**(1), 266–274.
23. DICKSON, Martha A., LENNON, Sharron J., MONTALTO, Catherine P., SHEN, Dong, ZHANG, Li. Chinese consumer market segments for foreign apparel products. *Journal of Consumer Marketing*, 2004, **21**(5), 301–317, doi: 10.1108/07363760410549131.
24. PERČIĆ, Karolina, PERČIĆ, Nenad, KUTLAČA, Đuro. The adoption of internet media as marketing innovations in Serbia. *Management,* 2019, **24**(2), doi: 10.7595/management.fon.2018.0032.
25. PORTOLESE, Dias, Laura. Generational buying motivations for fashion. *Journal of Fashion Marketing and Management: An International Journal*, 2003, **7**(1), 78–86, doi: 10.1108/13612020310464386.
26. COLE, Catherine, LAURENT, Gilles, DROLET, Aimee, EBERT, Jane, GUTCHESS, Angela, LAMBERT-PANDRAUDAT, Raphaëlle, MULLET, Etienne, NORTON, Michael I., PETERS, Ellen. Decision-making and brand choice by older consumers. *Marketing Letters*, 2008, **19**(3–4), 355–365.
27. WELLS, William D., GRUBAR, George. Life cycle concept in marketing research. *Journal of Marketing Research*, 1996, **3**(4), 355–363, doi: 10.2307/3149851.
28. SLIJEPČEVIĆ, M. Contemporary concept of fashion marketing. *Proceedings of the International Economics and Management Conference ECIN*, 2016.
29. BEJATOVIĆ, Gordana, MAMULA NIKOLIĆ, Tatjana. Inovacije kao ključni faktor u razvoju elektronske trgovine. *V Proceedings of the Inovacije kao inicijator razvoja* - MEFkon, 2018, pp. 348–366.
30. MAMULA, Tatjana. Izazov i šanse: razumevanje generacije Y. V *Zbornik radova HR konferencija. Upravljanje kvalitetom ljudskih resursa - savremeni trendovi*. UdEkoM Balkan, 2016.
31. ANIĆ, Ivan-Damir, MIHIĆ, Mirela. Demographic profile and purchasing outcomes of fashion conscious consumers in Croatia. *Ekonomski pregled*, 2015, **66**(2), 103–118.
32. WAARTS, Eric, van EVERDINGEN, Yvonne M. Fashion retailers rolling out across multi-cultural Europe. *International Journal of Retail & Distribution Management*, 2006, **34**(8), 645–657, doi: 10.1108/09590550610675958.

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Effect of Using Lower Linear Density Bobbin Thread on Seam Strength

Vpliv manjše dolžinske mase čolnične niti na trdnost šiva

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Abstract

Needle thread loses significant strength when incorporated into the seam. The needle thread being weaker tends to fail under load which results in a catastrophic failure of the seam. The use of a lower linear density bobbin thread is suggested in order to balance out the loss in the needle thread, which can help improve the production efficiency without compromising the seam strength. In this paper, four combinations of needle/bobbin threads are used at various process parameters to study the impact of a lower linear density bobbin thread on the seam strength. The seam strength prediction in such an asymmetrical combination of the needle and bobbin thread is also a subject of exploration in this paper as previous research has only taken place in an ideal situation where the same needle and bobbin threads were used.
Keywords: seam strength, loop strength, thread strength loss, stitch density

Izvleček

Igelna nit izgubi precejšen del trdnosti, ko je vgrajena v šiv. Pod vplivom obremenitve se bo igelna nit z nižjo trdnostjo prej pretrgala, kar lahko povzroči katastrofalen pretrg šiva. Pri uporabi čolnične niti z manjšo dolžinsko maso bi bile uravnotežene poslabšane lastnosti igelne niti, kar bi pripomoglo k izboljšanju učinkovitosti proizvodnje, ne da bi se pri tem poslabšala trdnost šiva. Članek proučuje vpliv manjše dolžinske mase čolnične niti na trdost šiva pri uporabi štirih različnih kombinacij igelnih in čolničnih niti in pri različnih procesnih parametrih. Predmet te raziskave je tudi napovedovanje trdnosti šiva pri uporabi različnih kombinacij igelnih in čolničnih niti, saj so bile dosedanje raziskave izvedene pri idealnih pogojih, ko sta čolnična in igelna nit enaki.
Ključne besede: trdnost šiva, trdnost zanke, izguba trdnosti niti, gostota šiva

1 Introduction

The characteristic parameters of the seam are its strength, puckering, stiffness, appearance and efficiency [1]. According to many researchers [2], there are various factors affecting the seam quality, e.g. sewing thread, sewing condition etc. However, the sewing thread size is the most crucial factor for the apparel seam stability, as an improper use of the seam thread size affects directly the seam quality of apparel. A good sewing thread should give satisfactory sewing and seam performance. The sewing performance of threads is generally assessed by studying the dynamic tension and the strength reduction of the thread [3, 4]. During the sewing, the needle thread is subjected to friction and tensile, bending, compressive, shear and surface stresses while passing through the machine elements and fabric assembly, leading to the loss in strength [5, 6]. The extent of strength reduction is a function of the magnitude of stresses acting on the threads and their ability to withstand the degrading effect of stresses [7]. The reduction in thread strength is a consequence of changes in the mechanical properties of fibres, of dynamic loading and/or of the changes in the thread structure [8]. Various researchers have observed that the extent of

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these stresses and friction is higher on the needle thread as compared to the bobbin thread. A typical cotton sewing thread may show a 20–30% loss in the needle thread as compared to the 8–10% loss in the bobbin thread depending upon various process parameters [5]. Due to different losses in the needle and bobbin thread during the sewing, the needle thread becomes weaker and may fail under these stresses, resulting in seam failure. Further, the imbalance in the strength of the needle thread and bobbin thread is expected to affect the seam strength as well. Therefore, in this paper, cotton and polyester threads with lower linear density were used as the bobbin thread, whereas cotton and polyester threads with higher linear density were used as the needle thread. It is expected that the needle thread loses more strength during the sewing; therefore, the needle thread strength after the sewing should match the bobbin thread strength after the sewing. The use of a lower linear density thread gives higher length of the thread in the bobbin, which consequently reduces the frequency of bobbin changes. Moreover, the seam strength prediction can also be improved by understanding the role of these stresses during the sewing process.

2 Materials and methods

Mercerized spun cotton thread of linear density 30 tex, 40 tex and 60 tex, and spun polyester thread of linear density 27 tex, 40 tex and 60 tex were used to prepare seams on 250 g/m^2 and 350 g/m^2 denim fabric with right hand twill (100% cotton) at different stitch densities, i.e. 8, 10 and 12 stitches/25.4 mm. The threads are characterized with the number of plies, twist direction, and twist and tensile properties as shown in Table 1.
The physical properties of fabrics are shown in Table 2. The breaking strength of the fabric was tested warp-wise as per ASTM D 5035(Strip test) on a Tinius Olson universal testing machine. The transverse seam strength was tested warp-wise in line with ASTM D1683.
The sewing thread tensile test was conducted on a universal testing machine (Tinius Oleson) at the gauge length of 250 mm according to the ASTM standard D2256 using the test speed which corresponds to 20 s breaking time. The sewing threads were also tested for loop strength in accordance with the ASTM standard D2256 at the 250 mm gauge length. The loop strength testing was done for different combinations of loops formed using

Table 1: Physical properties of sewing threads

Thread type	Linear density [tex]	Number of plies	Twist direction: single/ply	Twist [1/m]	Tenacity [cN/tex]	Breaking elongation [%]	Initial modulus [cN/tex]
Spun cotton	30	3	S/Z	840	25.7	5.15	586
	40	3	S/Z	707	33.2	7.18	546
	60	3	S/Z	597	31.4	7.95	366
Spun polyester	27	2	S/Z	689	20.9	14.22	205
	40	2	S/Z	711	36.9	14.68	154
	60	2	S/Z	590	34.9	17.01	132

Table 2: Physical properties of fabrics

Fabric density [g/m^2]	Weave pattern	Fabric thickness [mm]	Ends/cm	Picks/cm	Warp linear density [tex]	Weft linear density [tex]	Fabric strength [N]
250	2/1 RHT[a)]	0.67	25.98	18.11	49.16	49.16[b)]	328.55
350	2/1 RHT[a)]	0.82	27.16	18.11	65.55	65.55[b)]	395.29

[a)] Right hand twill
[b)] Open-end yarn

threads of different linear densities as shown in Table 3. The statistical t-test at 95% confidence level was performed for loop strength. A Juki industrial lockstitch sewing machine was run at the speed of 3000 stitches/min for the seam preparation using different linear densities of threads in the needle and bobbin as shown in Table 3. The seam strength testing was carried out as per ASTM standard 1683. The fabrics were stitched along the warp direction, which is the most common for garment seams. Moreover, the statistical t-test at 95% confidence level was conducted for seam strength (Table 3).

The thread profile in the seam resembles a loop and tends to have a similar failure mechanism; hence, the seam strength was calculated by multiplying the loop strength of threads and the number of loops that contribute to the seam strength. The seam strength prediction was done for all the thread combinations using equation 1 [5]. It was then compared with the experimental seam strength (Figures 1a and 1b).

$$\text{Estimated seam strength (N)} = \text{Stitch density (stitches/25 mm)} \times \text{Loop strength (N)} \quad (1)$$

3 Results and discussion

3.1 Effect of linear density of threads on thread loop strength

Table 3 shows the seam strength values for two different types of fabrics using different needle and bobbin thread combinations sewn at different stitch densities. It was observed that the seam strength at the 30 tex/30 tex: needle thread/bobbin thread (cotton) combination was lower than at other combinations of threads in the set, i.e. 30 tex/40 tex: needle thread/bobbin thread (cotton), 40 tex /30 tex: needle thread/bobbin thread (cotton) thread. The 40 tex/40 tex: needle thread/bobbin thread (cotton) combination showed significantly higher seam strength due to stronger threads showing higher loop strength. In the 30 tex/40 tex: needle thread/bobbin thread (cotton) combination or 40 tex/30 tex: needle thread/bobbin thread (cotton) combination, the higher seam strength is attributed to the higher loop strength of the combination. It was observed that the loop strength of the 30 tex/30 tex: needle thread/bobbin thread (cotton) combination was 1354 cN and that of 40 tex/40 tex: needle thread/bobbin thread (cotton) 2298 cN, whereas the loop strength of the 30 tex/40 tex: needle thread/bobbin thread (cotton) combination was 1452 cN. Using a thread with higher linear density in combination with a thread with lower linear density increased the loop strength of the thread marginally, which was statistically significant at 95% confidence level (Table 3). During the loop strength testing, the stress concentration was on the intersection point of the loops, which leads to the failure of loops from the point of stress concentration [9, 10].

3.2 Effect of linear density of threads on seam strength

The seam strength of the seam assembly made of threads with different linear densities in the needle and bobbin were tested as well, and the results are shown in Table 3. It was observed that the seam strength at the 40 tex/30 tex: needle thread/bobbin thread (cotton) combination was higher than at the30 tex/40 tex: needle thread/bobbin thread (cotton) combination for both fabrics. The same trend was observed at other combinations, i.e. at 60 tex/40 tex threads, although the trend was statistically significant in only few cases. This is due to the seam and loop strengths being dependent on the strength of the weaker thread, i.e. 30 tex. The loop failure is the reason for the seam failure in an ideal condition where all the loops are evenly stressed [11]. During the sewing process, the needle thread is exposed to higher stresses during the passage through the machine, as compared to bobbin thread. The needle thread gets more damage as compared to the bobbin thread. According to literature, the cotton needle thread loses 25–30% of strength, whereas the cotton bobbin thread loses only 8–10% of strength during the sewing process. When a 30 tex thread was used as the needle thread and 40 tex as the bobbin thread, the 30 tex needle thread lost more strength and the seam strength hence depended on the 30 tex thread, which further weakened. On the other hand, when a 30 tex thread was used as the bobbin thread and 40 tex thread was used as the needle thread, the 40 tex needle thread became weaker and lost more strength as compared to the 30 tex bobbin thread, and at the time of loading of loops during the seam strength testing, both threads had similar strengths and therefore showed higher strength as compared to the 30 tex/40 tex: needle thread/bobbin thread combination. The same trends were observed for the combinations of 60 tex/40 tex: needle thread/bobbin thread (cotton), 40 tex/27 tex: needle thread/bobbin thread (polyester) and 60 tex/40 tex: needle thread/bobbin thread (polyester).

3.3 Comparing experimental seam strength with estimated seam strength using loop strength of different linear densities of threads

The seam strength values were calculated with equation 1, using the loop strength values for different

Table 3: Seam strength at different combinations of needle and bobbin thread

Set	Needle-bobbin thread combination	Needle thread [tex]/bobbin thread [tex]	Thread type	Loop strength [cN]	Seam strength [N]/CV [%]					
					Denim fabric – 250 g/m^2			Denim fabric – 350 g/m^2		
					Stitch density [stitches/25.4 mm]			Stitch density [stitches/25.4 mm]		
					12	10	8	12	10	8
1	1	30/30	Cotton	1354	134/1.93	118/5.05	106/5.34	153/11.65	119/2.50	100/7.90
	2	30/40	Cotton	1452[a)]	167[a)]/4.95	132/8.09	111/5.10	162/8.51	127/10.54	111/3.97
	3	40/30	Cotton	1452	178[c)]/4.32	146[c)]/6.45	97[b)]/5.93	164/6.83	138[c)]/6.85	114/2.87s
	4	40/40	Cotton	2298[d)]	205[d)]/9.64	189[d)]/6.82	143[d)]/6.03	212[d)]/7.38	188[d)]/8.46	145[d)]/7.22
2	1	40/40	Cotton	2298	205/9.64	189/6.82	143/6.03	212/7.38	188/8.46	145/7.22
	2	40/60	Cotton	2438[a)]	211/4.82	190/4.26	150/1.97	208/3.81	190/6.99	137/6.88
	3	60/40	Cotton	2438	222/6.82	198/6.03	163[c)]/7.38	236[b, c)]/8.46	208/7.22	165[b)]/5.35
	4	60/60	Cotton	3237[d)]	277[d)]/2.66	267[d)]/3.24	250[d)]/2.03	342[d)]/2.72	271[d)]/1.49	227[d)]/3.55
3	1	27/27	Polyester	1083	114/11.55	100/8.18	85/5.86	127/10.89	85/8.72	82/9.64
	2	27/40	Polyester	1290[a)]	139[a)]/9.45	121[a)]/5.85	99[a)]/2.37	150[a)]/6.50	137[a)]/7.04	97[a)]/6.97
	3	40/27	Polyester	1290	158[c)]/5.95	141[b, c)]/8.47	104[c)]/9.62	170[c)]/15.52	130[c)]/8.66	103[c)]/4.03
	4	40/40	Polyester	2209[d)]	264[d)]/3.47	216[d)]/6.43	173[d)]/5.33	227[d)]/2.40	212[d)]/6.99	177[d)]/4.88s
4	1	40/40	Polyester	2209	264/3.47	216/6.43	173/5.33	227/2.40	212/6.99	176/4.88
	2	40/60	Polyester	2533[a)]	269/0.82	227/4.14	177/4.87	262[a)]/2.23	230[a)]/6.72	186/3.02
	3	60/40	Polyester	2533	248[b)]/3.94	241[c)]/4.57	159[b)]/6.77	289[b, c)]/7.24	231[c)]/2.96	184/4.74
	4	60/60	Polyester	3224[d)]	294[d)]/5.53	288[d)]/4.48	257[d)]/3.73	326[d)]/2.50	275[d)]/3.32	258[d)]/4.26

[a)] Significant w.r.t. combination 1 at same process parameters at 95% confidence level, [b)] Significant w.r.t. combination 2 at same process parameters at 95% confidence level, [c)] Significant w.r.t. combination 1 at same process parameters at 95% confidence level, [d)] Significant w.r.t. combinations 1, 2, 3 at 95% confidence level, Where w.r.t. stands for “with respect to”

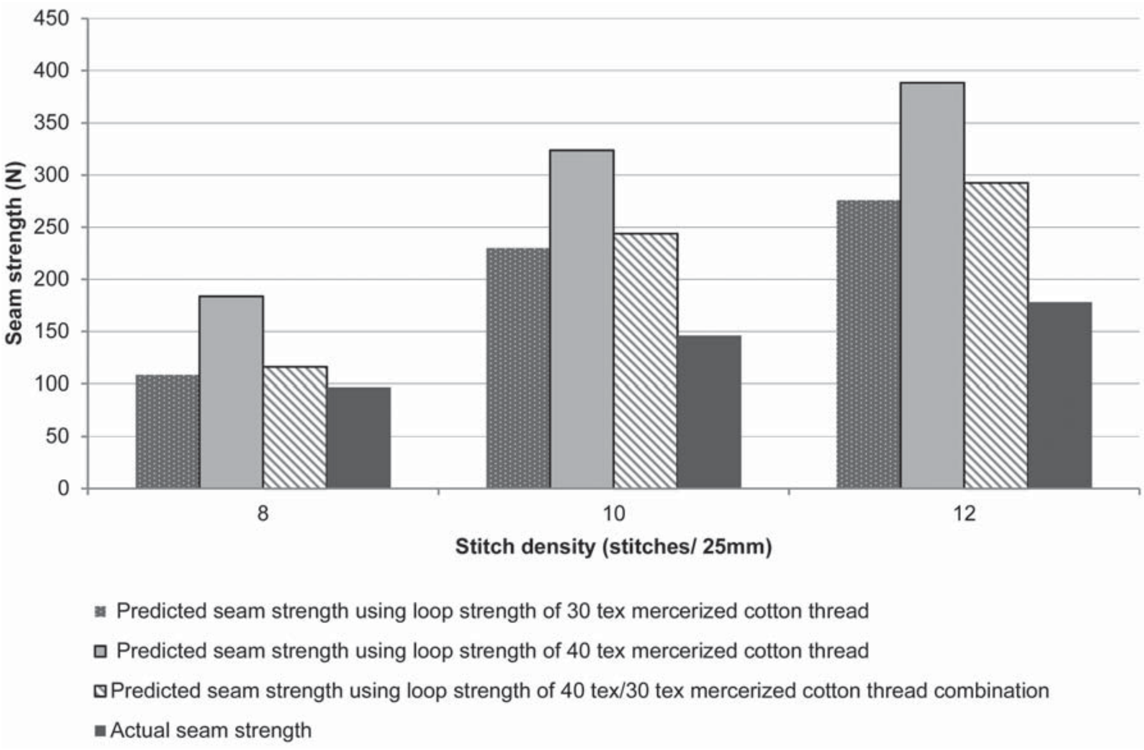

Figure 1: Experimental seam strength vs predicted seam strength for 40 tex/30 tex (needle/bobbin) spun cotton thread combination on 250 g/m² denim fabric

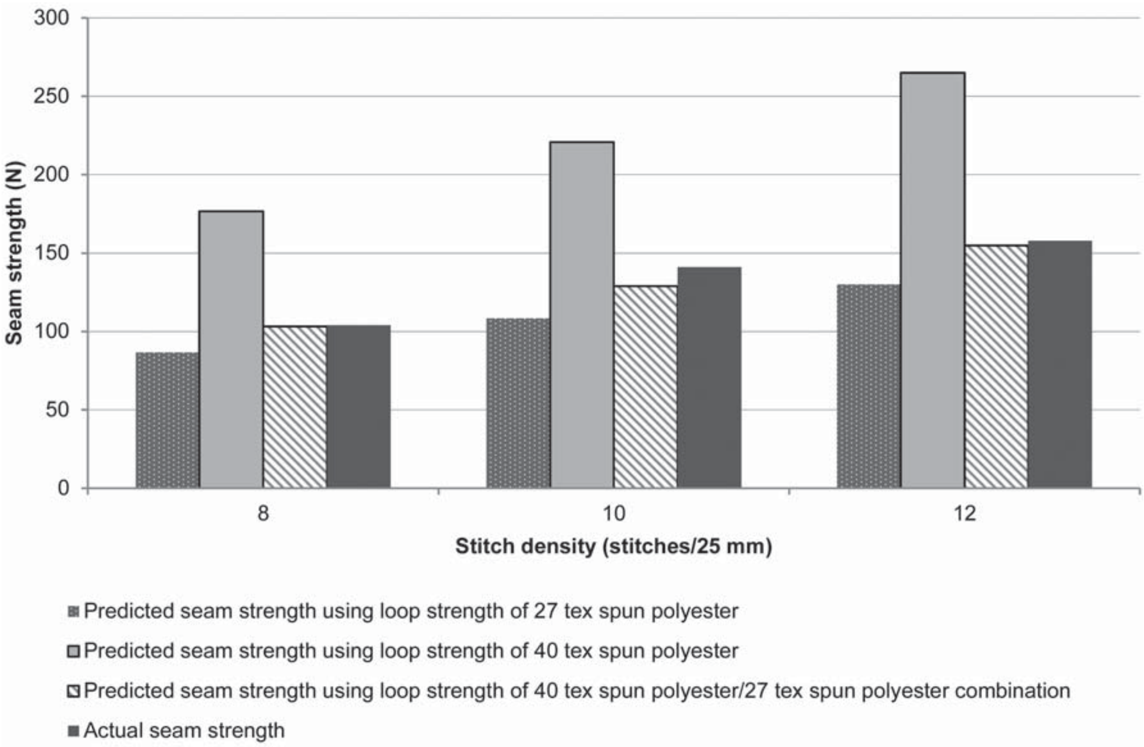

Figure 2: Experimental seam strength vs predicted seam strength for 40 tex/27 tex (needle/bobbin) spun polyester thread combination on 250 g/m² denim fabric

combinations of needle/bobbin threads, i.e. using loop strength of 30 tex cotton, using loop strength of 40 tex cotton thread and using loop strength of 40 tex/30 tex threads taken together. Similarly, the seam strength values for polyester threads were estimated as well. The calculated seam strength values were compared with the experimental seam strength values to find out the loop strength combination that gives a closer estimate of the seam strength. Figure 1 demonstrates that there is a significant difference between the experimental and predicted seam strength for the 40 tex/30 tex: needle/bobbin (cotton) thread combination at the stitch densities of 10 and 12, while the difference is lower at 8 stitches/25 mm. This may be a combined effect of increased thread strength loss and fabric damage due to higher stitch density. The seam strength estimation was closer to the experimental values when the loop strength of the thread with lower linear density, i.e. 30 tex cotton thread, or loop strength of 40 tex/30 tex: needle thread/bobbin thread was taken. Moreover, the same trend was observed at the 60 tex/40 tex: needle/bobbin cotton thread combination. At the 40 tex/27 tex: needle/bobbin spun polyester thread combination, the experimental seam strength was very close to the estimated seam strength calculated using the loop strength of 40 tex/27 tex: needle/bobbin spun polyester thread (Figure 2). The same trend was observed at the 60 tex/40 tex: needle/bobbin spun polyester thread combination also at different stitch densities, which results from the thread damage during the sewing being very low in the case of polyester threads. Consequently, the loop strength is directly reflected into the seam strength at different stitch densities at the polyester thread.

4 Conclusion

The seam strength increases with the use of a higher linear density (higher strength) thread in the needle and bobbin, which is due to the increased average loop strength compared to lower linear density threads in the needle and bobbin. When different threads are used in the needle and bobbin, the seam assembly where a higher linear density thread is used in the needle and a lower linear density thread is used in the bobbin shows higher seam strength compared to the seam assembly where a lower linear density thread is used in the needle and a higher linear density thread in the bobbin. Since the needle thread is exposed to various stresses during the passage through the machine and the bobbin thread experiences lower stresses, the needle thread gets more damaged as compared to the bobbin thread. The loss in the tensile properties of the needle thread is reflected in the seam strength values of a fabric. The use of a lower linear density thread in the bobbin significantly reduces the seam strength as compared to higher linear density threads in both the needle and bobbin; however, the predicted seam strength values are substantially higher than the actual seam strength values. Since polyester threads undergo less damage during the sewing process, the actual seam strength values are closer to the predicted values when a lower linear density thread is used as the bobbin thread.

References

1. DOBILAITE, Vaida, JUCIENE, Milda. The influence of mechanical properties of sewing threads on seam pucker. *International Journal of Clothing Science and Technology*, 2006, **18**(5), 335–345.
   doi: 10.1108/ 09556220610685276.
2. MERIC, B., DURMAZ, A. Effect of thread structure and lubrication ratio on seam properties. *Indian Journal of Fibre and Textile Research*, 2005, **30**(3), 273–277.
3. MIDHA, Vinay Kumar, KOTHARI, V. K., CHATTOPADHYAY, R., MUKHOPADHYAY, Arunaganshu. Effect of high-speed sewing on the tensile properties of sewing threads at different stages of sewing. *International Journal of Clothing Science and Technology*, 2009, **21**(4), 217−238, doi: 10.1108/09556220910959981.
4. MIDHA, Vinay Kumar, MUKHOPADHYAY, Arunangshu, CHATTOPADHYAY, R., KOTHARI, V. K. Studies on the changes in tensile properties of sewing thread at different sewing stages. *Textile Research Journal*, 2009, **79**(13), 1155−1167, doi: 10.1177/0040517508101456.
5. MIDHA, Vinay Kumar, MUKHOPADHYAY, Arunangshu, KAUR, Ramanpreet. An approach to seam strength prediction using residual thread strength. *Research Journal of Textile and*

Apparel, 2011, **15**(3), 75−85, doi: 10.1108/RJTA-15-03-2011-B009.
6. FERREIRA, F. B. N., HARLOCK, S. C., GROSBERG, P. A study of thread tensions on a lockstitch sewing machine (Part I). *International Journal of Clothing Science and Technology* 1994, **6**(1), 14−19, doi: 10.1108/09556229410054468.
7. SUNDARESAN, G., HARI, P. K., SALHOTRA, K. R. Strength reduction in sewing threads during high speed sewing in an industrial lockstitch machine: Part I - mechanism of thread strength reduction. *International Journal of Clothing Science and Technology,* 1997, **9**(5), 334−345, doi: 10.1108/09556229710185460.
8. RUDOLF, Andreja, GERŠAK, Jelka. Study of the relationship between deformation of the thread and built-in- fibers. *International Journal of Clothing Science and Technology,* 2001, **13**(¾,), 289−300, doi: 10.1108/EUM0000000005783.
9. MIDHA, Vinay Kumar, GUPTA, Ashish K, MUKHOPADHYAY, Arunaganshu. Effect of gauge length on loop strength of sewing threads. *The Journal of the Textile Institute*, 2018, **110**(3), 445−450, doi: 10.1080/00405000.2018.1489339.
10. RENGASWAMI, R. S., WESLEY, Samuel. Tensile behavior of sewing threads under simple- tensile, loop and knot tests. *Journal of Textile and Apparel, Technology and Management*, 2011, **7**(2), 1−21.
11. BRAIN, D. H. The prediction of strengths of lockstitch seams in woven fabrics. *Journal of Textile Institute,* 1970, **61**(10), 493−505, doi; 10.1080/00405007008630015.

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