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Influence of Accelerated Electron-Irradiation on Sorption Properties of Latvian Darkhead Sheep Wool Fibers

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Latvian Darkhead (LD) is a local sheep breed and a genetic resource in Latvia. Preservation and development of the sheep population in the local region is important for the recultivation of fields, it serves as a source for export and local use, as well as waste wool can be applied for developing new products, for example, sorbents for volatile organic pollutants. Therefore, investigation of the sorption properties of the LD sheep wool fibers is under interest. In addition, modification options of the wool for improvement of properties are viewed. Therefore, in the present work, sheep wool fibers as well as accelerated electron-irradiated fibers are analyzed and compared. Fourier transform infrared (FTIR) spectrometry is applied to develop the sorption testing system of volatile organic compounds. An analytical system consisting of a volatile organic compound source, sheep wool filter, and FTIR spectrometry cell is tested and applied for analysis of wool sorption properties for acetone molecules. Registration of the FTIR spectra was performed within the range of 600-4000 cm^{-1}, in the nitrogen flow of about 150mL/min. FTIR analysis shows, that the accelerated electron irradiated sheep wool fibers absorb acetone of about 33% more than non-irradiated fibers. The obtained results will be used for developing recommendations for filter producers to fabricate filter components containing LD sheep wool fibers.

Keywords: sheep wool, infrared spectrometry, electron irradiation, sorption.

1. INTRODUCTION

Only sheep wool fibers of high quality are utilized by the textile industry, while unprocessed sheep wool fibers often regrettably become waste at loading depots [1]. Non-textile sheep wool has found its place already as an insulating material [2], building additive [3, 4], keratin source [5], or fertilizer [6, 7]. However, still new applications are required, therefore ionizing radiation modifications can be applied [8, 9]. Absorbed doses up to 410 kGy [10 – 14] have been applied and shown to increase content of free radicals [15]. Among the applied irradiation types are 5 MeV accelerated electrons [16] and gamma rays (cobalt-60 source) [17]. Therefore, an absorbed dose of several hundred kGy can be selected for this work to perform comparable measurements to the previous studies. Previously, the time dependency of the various effects on wool has been investigated, for example, storage conditions [18] and post-irradiation changes [19]. It is proposed that sheep wool fibers can be applied in air filtrating systems [20 – 22]. However, for the first opinion, if the material has the potential for further applications as a filter, a rapid evaluation is required. Therefore, for the estimation of volatile organic compounds sorption capabilities in the wool, an approach involving Fourier transform infrared spectra (FTIR) registration is developed and exploited in the present work. As example for testing the FTIR method for sorption of volatile pollutants [23], acetone is selected that occurs in paint, pharmaceutical [24], and polymers processing [25, 26]. The application of recovery of vapors of volatile organic compounds from air is targeted to pollution control, and solvent recovery [27, 28]. Among the known acetone sorption systems are water columns [29], wood barks [30], polymer membranes [31], biochar [32], and activated carbon materials [33]. Sheep wool fibers are proposed for application in water filtrating systems [34] and air filters [35]. Therefore, to estimate the applications of the locally available source for air filtrating units, it is necessary to estimate its sorption behavior.

In the present work, a locally available [36, 37], renewable source, Latvian Darkhead (LD) sheep wool fibers are investigated. Fibers are irradiated with 10 MeV accelerated electrons and both, non-irradiated and irradiated wool, analyzed as potential filtering material for extraction of acetone molecules from gaseous flow of inert gas.

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2. EXPERIMENTAL

Latvian Darkhead (LD) sheep wool fibers, diameter of 25 ± 3 µm [18, 38], were cleaned and prepared for analysis by *Sunakstes vilnas nams* Ltd., Preparation involves washing of the cut wool, drying, and coursing to eliminate soil, dust and other impurities. Wool fibers were irradiated with 10 MeV accelerated electrons up to 500 kGy absorbed dose at room temperature in air at the Institute of Nuclear Chemistry and Technology (Warsaw, Poland) [39].

Chemical bonds in non-irradiated and electron irradiated wool fibers were analyzed by FTIR spectrometry, *Bruker Vertex 70v* spectrometer equipped with attenuated total reflection (ATR) module with a diamond crystal, ± 2cm^{-1}, 400 – 4000 cm^{-1}, 20 scans per spectrum, at least 10 measurements per sample.

Non-irradiated LD sheep wool fibers were exploited for testing the FTIR based sorption system, where the FTIR spectra profiles are used as indicators of the sorption analysis. The FTIR based sorption testing system includes the filter cartridge, volatile organic compound source and measuring cell for gaseous compounds (*Bruker Vertex 70v*, 600 – 4000 cm^{-1}, ± 4 cm^{-1}, Liquid Nitrogen-HgCdTe detector). A purge gas, nitrogen flow (*Linde gas* Ltd, 99.99 %) 150 mL/min guided through the cartridge to the spectrometer cell for a certain time (1.5 min), then the flow switched through the vapor of interest and FTIR spectra registered. Afterwards, the flow again changed to nitrogen. In the present work, acetone (*Sigma Aldrich*) vapor was used. The scheme of the measuring system is shown in Fig. 1.

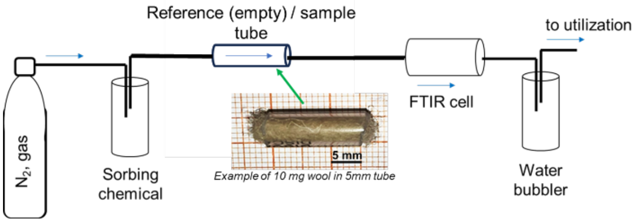

Fig. 1. Scheme of FTIR based sorption testing system for gaseous organic compounds

During the whole analysis (background measurement, insertion of the sorbing chemical, switching back to the background) the FTIR spectra are registered. The estimation of the sorption is performed by analyzing the intensity profile of the selected bond from the acetone spectrum. For the irradiated wool samples, the analysis was performed analogously as for non-irradiated.

3. RESULTS AND DISCUSSION

Chemical bonds of non-irradiated and electron irradiated sheep wool fibers were analyzed by means of FTIR-ATR. Afterwards, the fibers were incorporated into the FTIR based sorption testing system and tested for the sorption of acetone.

3.1. Analysis of fibers

Chemical bonds of the LD sheep wool fibers are analyzed using FTIR-ATR spectrometry. Since the fibrous structure is quite inhomogeneous, the intensities of the chemical bonds vary and only after summarizing information from several spectra, the overview of the ratios and the compositions of chemical bonds can be characterized. In Fig. 2, it is shown the variation of the spectra within the wool sample of about 1.0 g, where the aliquot for each measurement taken at about 0.1 mg and placed on ATR crystal. Similar variations in the spectra were observed in other samples as well [38]. The main peaks occur in the range of 400 – 1700 cm^{-1} and 2850 – 3300 cm^{-1}. The spectra correspond to the keratin-based [40] chemical structures, containing amide I and II vibrations around 1530 and 1640 cm^{-1} [41]. Sulphur containing bonds are in the range of 1020 and 1050 cm^{-1} [42]. Oxygen containing bonds in COH groups occur around 1400 – 1450 cm^{-1} [43]. Stretching vibrations of -CH_2 and -CH_3 groups are at 2850 and 2920 cm^{-1} [44]. Broad peaks around 3200 – 3600 cm^{-1} show to presence of primary amines [45].

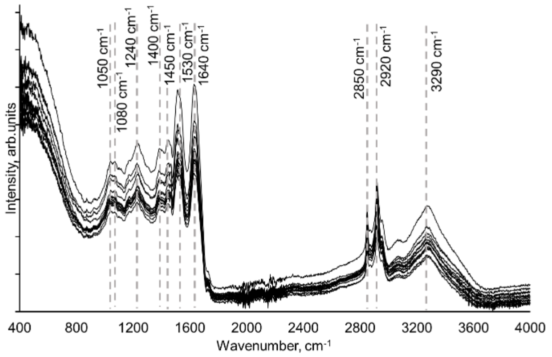

Fig. 2. FTIR-ATR spectra of non-irradiated LD wool fibers

The average spectrum of at least 10 spectra is calculated and compared to the electron irradiated wool spectrum. The average FTIR spectra on non-irradiated wool and electron irradiated wool are shown in Fig. 3. The spectra in Fig. 3 are placed on the shifted y axis for better resolution and visibility of the bonds.

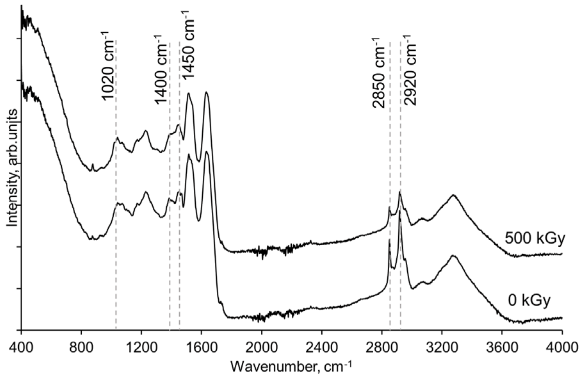

Fig. 3. Averaged FTIR-ATR spectra of non-irradiated (0 kGy) and electron irradiated (500 kGy) LD wool fibers

As can be seen from the obtained FTIR spectra, irradiation with 10 MeV accelerated electrons causes changes in some of the bonds and their intensities. In the electron irradiated wool fibers, the intensities of C-H bonds related signals at 2850 and 2920 cm^{-1} have been decreased. In spectra of non-irradiated wool peaks at 2850 and 2920 cm^{-1} are comparably higher than the nearby peaks of amine bonds. In irradiated wool intensities of 2850 and

2920 cm^{-1} peaks attributed to C-H bonds, have been decreased. Meanwhile, a slight increase of the signals at 1020, 1400 and 1450 cm^{-1} occurs that may correspond to -C-O- stretching and bending vibrations [46 – 48]. The changes in the spectra may be due to reorganization of the bonds [49], polymerization [50] or ozone [51] caused oxidation [52] of the functional groups in fibers.

Newly formed -CO bonds may act as capture centers for acetone molecules. In biochar, the acetone sorption mechanisms are based on large surface area and diffusion [53]. Surface condensation and hydrogen bond interactions are reported among the possible sorption mechanisms [54].

3.2. FTIR based sorption testing system for estimation of wool sorption properties

By applying FTIR based sorption testing system, the sorption properties of acetone in the non-irradiated and electron irradiated sheep wool fibers are evaluated. The measuring technique consists of two main stages, first where the measurement is performed with an empty filter cartridge. Nitrogen gas flow is guided through a cartridge and then acetone is introduced into the system. The FTIR spectra are recorded over a certain time and then the system is switched back to nitrogen flow. An example of measurement with acetone and an empty filter cartridge is shown in Fig. 4. A vibrational band with the maximal intensity for the reference spectrum, at 1753 cm^{-1}, assigned to the -C=O group in the ketone [55, 56], specific to the introduced reagent, is selected for analyzing the sorption efficiency.

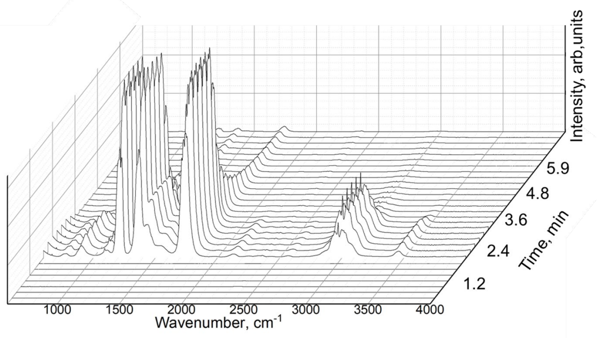

Fig. 4. FTIR spectra of acetone test through empty filter cartridge

The sorption profile of the acetone band at 1753 cm^{-1} on reference test, non-irradiated wool and electron irradiated wool is in Fig. 5.

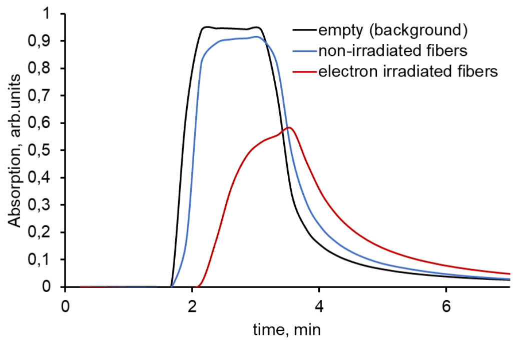

Fig. 5. Absorption profiles of 1753 cm^{-1} acetone stretching signal of acetone in the empty testing system and with the non-irradiated and electron irradiated sheep wool fibers

Normalizing the intensities to 1 and integrating the total band intensities to 100 %, it can be calculated that non-irradiated wool sorbs ~ 1 % of acetone molecules, while electron irradiated wool already ~33 % of the total amount of acetone. Electron irradiation created -C-O bonds, that were observed in FTIR-ATR spectra, can undergo physisorption interactions with sorbing molecules [57] causing the delayed signal in the FTIR spectra.

Therefore, the modifications of LD sheep wool with accelerated electrons can be applied to improve the sorption properties of the fibers. The changes in the sorption profile correspond to the changes in the chemical bond composition. Respectively – irradiation causes oxidation of the functional groups of the fiber structure, which further works as sorbing sites for -C=O functional groups containing molecules. Therefore, electron modified LD sheep wool fibers can be used as components in the air filtrating systems aimed for use in factories and other places, where the presence of acetone vapor is expected. In such a way the available, renewable source, LD sheep wool has a perspective application in air filtrating systems.

4. CONCLUSIONS

An absorbed dose of 500 kGy of accelerated electrons induces changes in the chemical bonds of LD sheep wool fibers, causing a decrease in intensities of -CH signals and the formation of -CO containing sites. Changes in the chemical bonds are followed by increased sorption capability of acetone molecules that are detected by the FTIR method. As result, the FTIR method can be applied as a rapid sorption estimation method. As well as determined acetone sorption can be further used as a beneficiary effect for applying electron irradiated sheep wool fibers as components in the air filtrating systems.

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REFERENCES

1. **Petek, B., Marinšek Logar, R.** Management of Waste Sheep Wool as Valuable Organic Substrate in European Union Countries *Journal of Material Cycles and Waste Management* 23 2021: pp. 44 – 54. https://doi.org/10.1007/s10163-020-01121-3
2. **Parlato, M.C.M., Porto, S.M.C., Valenti, F.** Assessment of Sheep Wool Waste as New Resource for Green Building Elements *Building and Environment* 225 2022: pp. 109596. https://doi.org/10.1016/j.buildenv.2022.109596
3. **Denes, O., Florea, I., Manea, D.L.** Utilization of Sheep Wool as a Building Material *Procedia Manufacturing* 32 2019: pp. 236 – 241. https://doi.org/10.1016/j.promfg.2019.02.208
4. **Alyousef, R., Mohammadhosseini, H., Ebid, A.A.K., Alabduljabbar, H.** An Integrated Approach to Using Sheep

Wool as a Fibrous Material for Enhancing Strength and Transport Properties of Concrete Composites *Materials (Basel)* 15 (5) 2022: pp. 1638. https://doi.org/10.3390/ma15051638

5. **Berechet, M., Simion, D., Stanca, M., Alexe, C.A., Ciprian, C., Rapa, M.** Keratin Hydrolysates Extracted from Sheep Wool with Potential Use as Organic Fertilizer *Leather and Footwear Journal* 20 2020: pp. 267 – 276. https://doi.org/10.24264/lfj.20.3.5

6. **Abdallah, A.M., Ugolini, F., Baronti, S., Maienza, A., Ungaro, F., Camilli, F.** Assessment of Two Sheep Wool Residues from Textile Industry as Organic Fertilizer in Sunflower and Maize Cultivation *Journal of Soil Science and Plant Nutrition* 19 2019: pp. 793 – 807. https://doi.org/10.1007/s42729-019-00079-y

7. **Gillespie, G., Dada, O., Mcdonnell, K.** The Potential for Hydrolysed Sheep Wool as a Sustainable Source of Fertiliser for Irish Agriculture *Sustainability* 14 (365) 2021: pp. 1 – 12. https://doi.org/10.3390/su14010365

8. **Porubska, M., Jomova, K., Lapcik, L., Braniša, J.** Radiation-modified wool for adsorption of redox metals and potentially for nanoparticles *Nanotechnology Reviews* 9 2020: pp. 1017 – 1026. https://doi.org/10.1515/ntrev-2020-0080

9. **Hanzlíková, Z., Braniša, J., Jomova, K., Fülöp, M., Hybler, P., Porubská, M.** Electron Beam Irradiated Sheep Wool – Prospective Sorbent for Heavy Metals in Wastewater *Separation and Purification Technology* 193 2018: pp: 345 – 350. https://doi.org/10.1016/j.seppur.2017.10.045

10. **Podjava, A., Zarins, A., Avotina, L., Shvirksts, K., Baumane, L., Rasmane, D.A., Grube, M., Kizane, G.** Latvian Sheep Wool Fiber as a Cheap Natural Adsorbent for the Removal of Congo Red Dye from Wastewater *Water, Air, and Soil Pollution* 233 (11) 2022: pp. 451. https://doi.org/10.1007/s11270-022-05915-z

11. **Porubska, M., Koosova, K., Branisa, J.** Competitive Cation Adsorption on Electron-Irradiated Sheep Wool Changes the Fitting of Adsorption Isotherms for Single-Component Solutions *Processes* 11 (502) 2023: pp. 1 – 23. https://doi.org/10.3390/pr11020502

12. **Braniša, J., Kleinová, A., Jomová, K., Weissabel, R., Cvik, M., Branišová, Z., Porubská, M.** Sheep Wool Humidity under Electron Irradiation Affects Wool Sorptivity towards Co(II) Ions *Molecules* 26 (17) 2021: pp. 5206. https://doi.org/10.3390/molecules26175206

13. **Hanzlíková, Z., Braniša, J., Hybler, P., Šprinclová, I., Jomova, K., Porubska, M.** Sorption Properties of Sheep Wool Irradiated by Accelerated Electron Beam *Chemical Papers* 70 (9) 2016: pp. 1299 – 1308. https://doi.org/10.1515/chempap-2016-0062

14. **Braniša, J., Jomová, K., Lapčík, L., Porubská, M.** Testing of Electron Beam Irradiated Sheep Wool for Adsorption of Cr(III) and Co(II) of Higher Concentrations *Polymer Testing* 99 2021: pp. 107191. https://doi.org/10.1016/j.polymertesting.2021.107191

15. **Braniša, J., Kleinová, A., Jomová, K., Malá, R., Morgunov, V., Porubská, M.** Some Properties of Electron Beam-Irradiated Sheep Wool Linked to Cr(III) Sorption *Molecules* 24 (23) 4401 2019: pp. 1 – 19. https://doi.org/10.3390/molecules24234401

16. **Porubská, M., Hanzlíková, Z., Braniša, J., Kleinová, A., Hybler, P., Fülöp, M., Ondruška, J., Jomová, K.** The Effect of Electron Beam on Sheep Wool *Polymer Degradation and Stability* 111 2015: pp. 151 – 158. https://doi.org/10.1016/j.polymdegradstab.2014.11.009

17. **Rapakgadi, J., Hunter, L., Nothnagel, G., Botha, A.** Effect of Gamma Radiation on Greasy and Scoured Wool, Irradiated in Mini-Bale Form *Journal of Natural Fibers* 19 (7) 2022: pp. 2567 – 2580. https://doi.org/10.1080/15440478.2020.1821279

18. **Avotina, L., Zarins, A., Nesenbergs, J., Vanags, E., Lescinskis, A., Ansone, A., Selga, T., Baryshev, A., Kizane, G.** Impact of Storage Conditions on Preparation of Activated Carbon from Sheep Wool Fibres *Agronomy Research* 21(X) 2023: pp. xxx – ccc. https://doi.org/10.15159/AR.23.062

19. **Hanzlíková, Z., Lawson, M.K., Hybler, P., Fülöp, M., Porubská, M.** Time-Dependent Variations in Structure of Sheep Wool Irradiated by Electron Beam *Advances in Materials Science and Engineering* 2017 2017: pp. 1 – 10. https://doi.org/10.1155/2017/3849648

20. **Xiang, H., Wang, Y.J., Di, Y.H.,** Experimental Study of Wool Fiber on Purification of Indoor Air *Textile Research Journal* 77 (12) 2007: pp. 946 – 950. https://doi.org/10.1177/0040517507083519

21. **Gustavsson, J.** New Developments in air Filter Test Methods and Classification *Filtration & Separation* 33 (2) 1996: pp. 0 – 154. https://doi.org/10.1016/s0015-1882(97)84207-3

22. **Su, Y., Sun, L.** A Comparative Study of Permeable and Semipermeable Membranes Constructed Multiple Layer Water Filters by Non-Dimensional Lattice Boltzmann Simulations *International Journal of Heat and Mass Transfer* 119 2018: pp. 77 – 90. https://doi.org/10.1016/j.ijheatmasstransfer.2017.11.105

23. **Vincent, G., Schaer, E., Marquaire, P.M., Zahraa, O.** CFD Modelling of an Annular Reactor, Application to the Photocatalytic Degradation of Acetone *Process Safety and Environmental Protection* 89 (1) 2011: pp. 35 – 40. https://doi.org/10.1016/j.psep.2010.08.004

24. **Enright, A.M., McHugh, S., Collins, G., O'Flaherty, V.** Low-temperature Anaerobic Biological Treatment of Solvent-Containing Pharmaceutical Wastewater *Water Research* 39 (19) 2005: pp. 4587 – 4596. https://doi.org/10.1016/j.watres.2005.08.037

25. **Liu, K., Schuch, F., Kiran, E.** High-pressure Viscosity and Density of Poly(Methyl Methacrylate)+Acetone and Poly(Methyl Methacrylate)+Acetone+CO_2 systems *The Journal of Supercritical Fluids* 39 (1) 2006: pp. 89 – 101. https://doi.org/10.1016/j.supflu.2005.12.018

26. **Zagorskis, A., Januševičius, T., Danila, V.** Removal of Acetone Vapor from Air Using a Biotrickling Filter Packed with Polymeric Bioballs *Processes* 10 (57) 2022: pp. 1 – 14. https://doi.org/10.3390/pr10010057

27. **Márki, E., Lenti, B., Vatai, G., Bekassy-Molnar, E.** Clean Technology for Acetone Absorption and Recovery *Separation and Purification Technology* 22 (23) 2001: pp. 377 – 382. https://doi.org/10.1016/S1383-5866(00)00121-0

28. **Sheokand, S., Modi, S.R., Bansal, A.K.** Dynamic Vapor Sorption as a Tool for Characterization and Quantification of Amorphous Content in Predominantly Crystalline Materials *Journal of Pharmaceutical Sciences* 103 (11) 2014: pp. 3364 – 3376. https://doi.org/10.1002/jps.24160

29. **Márki, E., Lenti, B., Vatai, G., Békássy-Molnár, E.** Clean technology for Acetone Absorption and Recovery *Separation and Purification Technology* 22 (3) 2001: pp. 377 – 382. https://doi.org/10.1016/S1383-5866(00)00121-0

30. **Zagorskis, A., Vaiškūnaitė, R.** An Investigation on the Efficiency of Air Purification Using a Biofilter with Activated Bed of Different Origin *Inzynieria Chemiczna i Procesowa* 35 2014: pp. 435 – 445. https://doi.org/10.2478/cpe-2014-0033

31. **Gales, L., Mendes, A., Costa, C.** Removal of Acetone, Ethyl Acetate and Ethanol Vapors from Air Using a Hollow Fiber PDMS Membrane Module *Journal of Membrane Science* 197 (1–2) 2002: pp. 211 – 222. https://doi.org/10.1016/S0376-7388(01)00628-7

32. **Švábová, M., Bičáková, O., Vorokhta, M.** Biochar as an Effective Material for Acetone Sorption and the Effect of Surface Area on the Mechanism of Sorption *Journal of Environmental Management* 348 (119205) 2023: pp. 1 – 9. https://doi.org/10.1016/j.jenvman.2023.119205

33. **Su, Z., Zhang, Y., Huang, L., Wang, S., Zhu, Y., Li, L., Lu, X.** Acetone Adsorption on Activated Carbons: Roles of Functional Groups and Humidity *Fluid Phase Equilibria* 521 (112645) 2020: pp. 1 – 9. https://doi.org/10.1016/j.fluid.2020.112645

34. **Pang, L., Lin, S., Krakowiak, J., Yu, S., Hewitt, J.** Performance Analysis of Sheep Wool Fibres as a Water Filter Medium for Human Enteric Virus Removal *Journal of Water Process Engineering* 47 (102800) 2022: pp. 1 – 6. https://doi.org/10.1016/j.jwpe.2022.102800

35. **McNeil, S., Zaitseva, L.** The Development of Wool-Based Passive Filters to Improve Indoor Air Quality *Key Engineering Materials* 671 2016: pp. 219 – 224. https://doi.org/10.4028/www.scientific.net/KEM.671.219

36. **Sjakste, T., Paramonova, N., Grislis, Z., Trapina, I., Kairisa, D.** Nucleotide Polymorphism in the 5′UTR and Part of Intron I of the Sheep MSTN Gene *DNA and Cell Biology* 30 2011: pp. 433 – 444. https://doi.org/10.1089/dna.2010.1153

37. **Trapina, I., Kairisa, D., Paramonova, N.** Comparison of Sire Rams of the Latvian Dark-Head Breed According to Feed Efficiency Indicators as the Beginning of Genomic Breeding Research *Agronomy Research* 21 (S2) 2023: pp. 598 – 610. https://doi.org/10.15159/AR.23.030

38. **Voikiva, V., Zarins, A., Avotina, L., Barmina, I., Rudovica, V., Kizane, G.** Influence of Biomass Combustion Products on Element Content and Thermal Stability of Latvian Sheep Breed Wool Filter Fibres *Materials Science* 26 2020: 438 – 443. https://doi.org/10.5755/j01.ms.26.4.23942

39. **Iuliano, A., Nowacka, M., Rybak, K., Rzepna, M.** The Effects of Electron Beam Radiation on Material Properties and Degradation of Commercial PBAT/PLA Blend *Journal of Applied Polymer Science* 137 (11) 2019: pp. 48462. https://doi.org/10.1002/app.48462

40. **Selmin, F., Cilurzo, F., Aluigi, A., Franzè, S., Minghetti, P.** Regenerated Keratin Membrane to Match the In Vitro Drug Diffusion Through Human Epidermis *Results in Pharma Sciences* 2 2012: pp. 72 – 78. https://doi.org/10.1016/j.rinphs.2012.10.001

41. **Sizeland, K., Hofman, K., Hallett, I., Martin, D., Potgieter, J., Kirby, N., Hawley, A., Mudie, S., Ryan, T., Haverkamp, R., Cumming, M.** Nanostructure of Electrospun Collagen: Do Electrospun Collagen Fibers Form Native Structures? *Materialia* 3 2018: pp. 90 – 96. https://doi.org/10.1016/j.mtla.2018.10.001

42. **Ramya, K.R., Thangam, R., Madhan, B.** Comparative Analysis of the Chemical Treatments Used in Keratin Extraction from Red Sheep's Hair and the Cell Viability Evaluations of this Keratin for Tissue Engineering Applications *Process Biochemistry* 90 2020: pp. 223 – 232. https://doi.org/10.1016/j.procbio.2019.11.015

43. **Zoccola, M., Aluigi, A., Patrucco, A., Vineis, C., Forlini, F., Locatelli, P., Sacchi, M.C., Tonin, C.** Microwave-assisted Chemical-Free Hydrolysis of Wool Keratin *Textile Research Journal* 82 (19) 2012: pp. 2006 – 2018. https://doi.org/10.1177/0040517512452948

44. **Patil, N., Netravali, A.** Enhancing Strength of Wool Fiber Using a Soy Flour Sugar-Based "Green" Cross-linker *ACS Omega* 4 2019: pp. 5392 – 5401. https://doi.org/10.1021/acsomega.9b00055

45. **Zain, N.F., Zainal, N., Mohamed, N.S.** The Influences of Ionic Liquid to the Properties of Poly(Ethylmethacrylate) Based Electrolyte *Physica Scripta* 90 2015: pp. 015702 – 015709. https://doi.org/10.1088/0031-8949/90/1/015702

46. **Vodnar, D., Pop, O.L., Socaciu, C.** Monitoring Lactic Acid Fermentation in Media Containing Dandelion (Taraxacum officinale) by FTIR Spectroscopy *Notulae Botanicae Horti Agrobotanici Cluj-Napoca* 40 (1) 2012: pp. 65 – 68. https://doi.org/10.15835/nbha4016653

47. **Sekaran, S., Devulapalli, S., Ambigapathi, M., Selvamurugan, N.** Chitosan Scaffolds containing Chicken Feather Keratin Nanoparticles for Bone Tissue Engineering *International Journal of Biological Macromolecules* 62 2013: pp. 481 – 486. https://doi.org/10.1016/j.ijbiomac.2013.09.034

48. **Coldea, T., Socaciu, C., Fetea, F., Ranga, F., Pop, R., Florea, M.** Rapid Quantitative Analysis of Ethanol and Prediction of Methanol Content in Traditional Fruit Brandies from Romania, using FTIR Spectroscopy and Chemometrics *Notulae Botanicae Horti Agrobotanici Cluj-Napoca* 41 2013: pp. 143 – 149. https://doi.org/10.15835/nbha4119000

49. **Porubska, M., Kleinova, A., Hybler, P., Braniša, J.** Why Natural or Electron Irradiated Sheep Wool Show Anomalous Sorption of Higher Concentrations of Copper(II) *Molecules* 23 (12) 3180 2018: pp. 1 – 15. https://doi.org/10.3390/molecules23123180

50. **Elbalasy, I., Wilharm, N., Herchenhahn, E., Konieczny, R., Mayr, S.G., Schnauss, J.** From Strain Stiffening to Softening—Rheological Characterization of Keratins 8 and 18 Networks Crosslinked via Electron Irradiation *Polymers* 14 (614) 2022: pp. 1 – 13. https://doi.org/10.3390/polym14030614

51. **Cleland, M.R., Galloway, R.A.** Ozone Generation in Air during Electron Beam Processing *Physics Procedia* 66 2015: pp. 586 – 594. https://doi.org/10.1016/j.phpro.2015.05.078

52. **Zhang, X., Gao, B., Zheng, Y., Hu, X., Creamer, A.E., Annable, M.D., Li, Y.** Biochar for Volatile Organic Compound (VOC) Removal: Sorption Performance and Governing Mechanisms *Bioresource Technology* 245 (A) 2017: pp. 606 – 614. https://doi.org/10.1016/j.biortech.2017.09.025

53. **Pan, B., Xing, B.** Adsorption Mechanisms of Organic Chemicals on Carbon Nanotubes *Environmental Science & Technology* 42 (24) 2008: pp. 9005 – 9013. https://doi.org/10.1021/es801777n

54. **Barshan, S., Pazirandeh, A., Jahanfarnia, G.** Measurement of Ozone Produced by 10 MeV Electron Accelerator Yazd in Various Currents *Journal of Instrumentation* 15 (01) 2020: pp. P01004 – P01004. https://doi.org/10.1088/1748-0221/15/01/P01004

55. **Ferrero, F., Mossotti, R., Innocenti, R., Coppa, F., Periolatto, M.** Enzyme-aided Wool Dyeing: Influence of Internal Lipids *Fibers and Polymers* 16 2015: pp. 363 – 369. https://doi.org/10.1007/s12221-015-0363-8

56. **Akiyama, Y., Fujita, S., Senboku, H., Rayner, C.M., Brough, S.A., Arai, M.** An *In Situ* High Pressure FTIR Study on Molecular Interactions of Ketones, Esters, and Amides with Dense Phase Carbon Dioxide *The Journal of Supercritical Fluids* 46 (2) 2008: pp. 197 – 205. https://doi.org/10.1016/j.supflu.2008.03.009

57. **Zhu, D., Kwon, S., Pignatello, J.J.** Adsorption of Single-Ring Organic Compounds to Wood Charcoals Prepared under Different Thermochemical Conditions *Environmental Science & Technology* 39 (11) 2005: pp. 3990 – 3998. https://doi.org/10.1021/es050129e