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Considerations in Recycling Research: Laboratory Practices for Fibrous and Plastic Materials at Russian and Uzbekistan Universities

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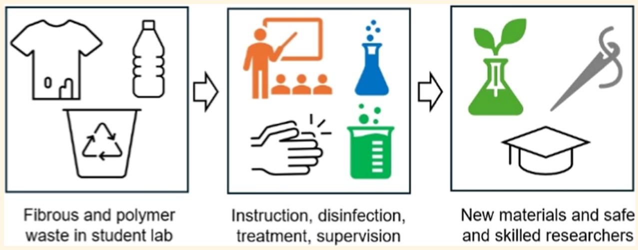
ABSTRACT: As the demand for sustainable recycling of fibrous and polymeric waste increases, university laboratories play a crucial role in developing new technologies while training future professionals. This study presents a practical model for conducting safe, student-led laboratory research on the chemical recycling of textile waste with a focus on silk and cotton materials. It outlines safety measures for managing chemical and biological hazards including waste classification, disinfection protocols, and risk assessment procedures adapted for educational settings. Key innovations include the use of express tests for verifying bacterial decontamination, tailored workspace organization, and the application of solvent-based cleaning for material purity, a general approach to laboratory management that emphasizes student and staff responsibilities to health and safety. The study also reviews regulatory compliance and engineering controls specific to Russian and Uzbekistan academic settings. The proposed approach, supported by case studies, demonstrates the safe engagement of students in meaningful recycling research while mitigating risks associated with fibrous waste handling and chemical processing under the guidance of staff members who are not specialist health and safety professionals.



KEYWORDS: *fibrous waste recycling, student laboratory safety, textile waste disinfection, sustainable education, waste classification, silk fibroin recycling, cotton dust control*

■ INTRODUCTION

The growing need to increase the share of recycling of fibrous materials and plastic waste is driven primarily by not only environmental but also economic and social factors. Increasing the volume of textile recycling, along with raising consumer awareness, is a key principle of sustainable development.[1] The global textile recycling market in 2024 reached \$6b, with annual growth trends of 4.9%.[2] Europe dominates textile waste processing, followed by USA, China, and other countries. Worldwide, including in Russia (per the Federal Circular Economy Project),[3] the industry faces the objective of maximizing the volume of reused products. Currently, only 1% of used textiles are recycled back into textile products,[4] and only 9% of plastics ever produced have been recycled, with the remaining either being used or disposed in landfills/released in oceans.[5] Russian regulatory targets for eco-collection require manufacturers to recycle at least 60% of textile waste and 65% of plastic waste by 2029.[6]

Recycling of fibrous material, fiber-forming polymer, and plastic waste involves either creating new materials (clothing, home/technical textiles, consumables)[7−12] or extracting useful components (monomers, oligomers, or polymers),[13,14] which conserves resources and raw materials. Depending on the type of waste, mechanical, thermomechanical, or chemical recycling processes are chosen, with mechanical recycling presenting the most economic benefit so far.[15] For example, polyester fiber products based on polyethylene terephthalate may be mechanically recycled via shredding to produce toy filling, concrete aggregate, and more,[16] thermally subjected to pyrolysis for hydrocarbon fuel,[17] or chemically processed (via hydrolysis, ammonolysis, methanolysis, and glycolysis) to yield monomers for further utilization in the production of new fibers, copolymers, or other value-added materials.[18−20] Similarly, polyethylene terephthalate (PET) waste is known to be commercially recycled both mechanically and chemically into resins, fibers, and flakes and into small molecules used as intermediates in future chemical synthesis.[21] Physicochemical

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recycling may also involve dissolution with the subsequent regeneration into new materials. This is especially suitable for natural polymers like cellulose[22,23] and silk fibroin,[24−26] as well as synthetic, solution-spinnable polymers like polyacrylonitrile.[27] Selective solvent extraction to purify polymers is another viable route of textile and plastic recycling.[21,28]

Due to the high importance, recycling technologies attract extensive academic interest and are embedded in university research and curricula.[21] Active research is conducted into efficient fiber and polymer material recycling technologies in academia. Such research involves undergraduate, master's, and PhD students. Thus, ensuring safety in chemical laboratories becomes particularly important due to researchers' varying levels of experience in both chemical practices and health and safety and inconsistent risk perception. Chemical recycling is very promising for converting fibrous and polymer waste into new materials; however, these technologies have strict necessity of safety measures when working with both chemicals and fibrous waste, a topic underrepresented in academic and regulatory contexts.

Universities worldwide maintain health and safety (H&S) functions, but their structure and scope vary. In the United States, universities generally operate Environmental Health and Safety (EH&S) departments that oversee occupational, laboratory, and environmental safety, often supported by departmental safety committees and integrated risk management frameworks. In the UK, universities typically have similar centralized H&S teams responsible for compliance, risk management, training, audits, and staff wellbeing. In Asia, there are also examples of dedicated H&S teams that oversee university-wide safety programs and compliance. In Western and Northern Europe, H&S responsibilities are often split between departmental safety officers and central offices, whereas in Southern Europe, compliance-focused safety officers are legally required but strategic oversight is less centralized. In Russia and other Eastern European countries, occupational safety departments primarily address regulatory compliance and accident prevention, monitoring staff safety training, conducting inspection, and auditing safety records. Laboratory and fire safety are usually handled separately, often by technical services or security divisions. To address H&S aspects during student laboratory practices and research, the first laboratory session is dedicated to familiarizing students with safety regulations. Students review the rules aloud, followed by a quiz addressing specific scenarios. All activities are recorded in a dedicated logbook and certified by the signatures of both the instructor and each student. Organizing student safety in Russian university chemical laboratories is crucial and is generally achieved through technical staff ensuring:

1. Implementation of safe working procedures in chemical laboratories, including ensuring compliance with fire safety regulations for scientific and educational institutions.[29]
2. Monitoring compliance with the university's internal procedures, including alignment of the research with the curriculum and approved learning objectives, lesson plans, and student conduct. These rules also take into account regulatory requirements for safe work in chemical laboratories.[30]
3. Monitoring compliance with rules for handling chemical substances, which are communicated to students before they are allowed to work in the laboratory, is essential and must be strictly maintained in accordance with local regulatory requirements.[31]
4. Mandatory familiarization of students with the emergency procedures (incidents involving chemicals, fire, etc.), raising their awareness of the risks and emergency response.

Apart from establishing procedures and their controls, the key laboratory safety requirements at a university include:

a Maintaining the general supply and exhaust ventilation and local exhaust ventilation (LEV) systems in working condition, an essential engineering control when working with chemical substances.

b Monitoring the integrity of laboratory glassware and equipment made of chemically resistant materials.

c Use of personal protective equipment, selected based on safety requirements for specific types of work.

Russian and Uzbekistan chemical safety protocols align with global standards, including the Basel Convention (for governing of transboundary movement of hazardous wastes),[32] Stockholm Convention on Persistent Organic Pollutants (Russia and Uzbekistan ratified the treaty in 2011 and 2019, respectively),[33] Montreal Protocol (which aims to protect the ozone layer by phasing out substances that deplete it),[34] and the Strategic Approach to International Chemicals Management (supported by the Ministry of Natural Resources and Environment in Russia and Ministry of Ecology and Environmental Protection in Uzbekistan).[35]

■ SPECIFIC CHALLENGES IN STUDENT LABORATORY RESEARCH

At Saint Petersburg State University of Industrial Technologies and Design (SPbSUTD), hands-on lab and research work is a fundamental part of chemistry curricula. Laboratory work is vital to preparing students and researchers for future careers. It is important to recognize that the potential hazards in university laboratories can be several times greater compared to industrial laboratories; however, the negative impact of an incident is usually minimized due to the smaller scales of the experiments.[36]

Primary safety challenges and controls in the laboratory are as follows:

1 Insufficient student awareness of the physical/chemical properties of laboratory reagents and their associated health and safety hazards

To address this, the study curriculum includes a dedicated course on occupational health and safety in laboratories, particularly targeted at first-year students at the beginning of each semester. Annual training sessions on laboratory safety are also provided for academic and technical staff. In addition, routine laboratory audits using standardized checklists are conducted to assess risks and identify and rectify safety violations. The training programs cover topics such as chemical safety, emergency response plans involving hazardous substances, and laboratory-specific safety protocols for staff. Particularly effective has been the application of a chemical risk assessment methodology described by Fatemi et al. (2022), which we adopted in our SPbSUTD laboratories.[37] According to this approach, among the commonly used chemicals in the teaching laboratory, hydrochloric acid poses the highest risk to health and the environment, while nitric

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Table 1. Classification of Solid Waste Hazard Levels[38]

hazard class	degree of environmental harm	examples
I (extremely hazardous)	very high: the ecological system is irreparably damaged; the recovery period is unknown	waste containing diphenyls, cresols, mineral oils
II (highly hazardous)	high: the ecological system is severely damaged; the recovery period is at least 30 years	waste containing lead salts
III (moderately hazardous)	medium: the ecological system is damaged; the recovery period is at least 10 years	waste containing motor oils
IV (low hazard)	low: the ecological system is damaged; the recovery period is at least 3 years	cellulose-containing waste, wool keratin, silk fibroin
V (virtually nonhazardous)	very low: the ecological system is almost undamaged	easily degradable shredded natural materials

acid, sulfuric acid, sodium hydroxide, and ethanol are classified as potentially hazardous. These reagents are stored separately from others and are issued to students only under strict supervision and logging procedures. Adopting this approach has led to a measurable reduction in reagent consumption and a decrease in the number of potentially hazardous incidents during their use. On average, pre-2024, one incident of varying severity used to occur each semester, including chemical spillages and chemical exposures, allergic reactions from chemicals or exposure to fibrous or polymeric waste, and dizziness from inhaling solvent vapors when working without recommended controls. There have been no such incidents recorded since the introduction of this risk assessment methodology, supported by enhanced student induction.

2 Improper storage and handling of volatile substances

These substances should be stored in specially designed stainless steel or durable glass containers and placed away from walkways and areas of frequent student movement. Refrigerated storage is recommended as it significantly reduces evaporation losses and inhalation exposure. Proper labeling of volatile substance containers not only improves organization but also highlights the associated hazards. For each new substance introduced, a dedicated risk assessment is recommended. This assessment is called "safety passport", and each reagent must have one.

3 Poorly organized workspaces

Case-study-based training before each new research project, with collective discussion, helps students properly design safe and efficient workspaces that minimize exposure to hazards and facilitate safe movement within the laboratory.

4 Lack of supervision, especially during the use of glassware and specialized equipment

To counteract this, the number of students per session is reduced, and all equipment setup and safe working practices are monitored directly by academic or technical members of staff. The number of incidents involving cuts from broken glassware has decreased by roughly 90% since students received additional training, and the maximum student-to-supervisor ratio has improved from 50:1 to 20:1. Undergraduate students rarely work completely unsupervised; however, graduate research may be conducted with minimal supervision.

5 Failure to/or incorrect use of suitable personal protective equipment (PPE) (lab coats, gloves, goggles, masks, etc.)

This is mitigated through group discussions on PPE effectiveness prior to each new experiment and a system of incentives and penalties, such as awarding additional marks for the correct selection and use of PPE during laboratory work.

It is a standard requirement that all laboratory personnel aged 18 and above who are authorized to handle waste, hazardous reagents, and disinfectants must undergo specialized training in personal and occupational safety, as well as periodic medical examinations, in accordance with the legislation of the Russian Federation. Student researchers permitted to work with fibrous waste receive comprehensive instruction and training in safe handling procedures and are only allowed to carry out disinfection activities under the direct supervision of qualified staff.

With regard to the specific aspects of handling waste derived from fibrous and polymeric materials, it is essential to consult the safety data sheets (SDS) of any new chemical substances and materials before introducing them into laboratory processes in order to understand their physicochemical, toxicological, and fire hazard properties. However, this information is often not available for waste material supplied for research purposes. In the Russian Federation, solid waste is classified according to an established system, with the characteristics summarized in Table 1. The classification of waste by the hazard class is based on the degree of its adverse impact on the environment. This includes both the intrinsic environmental hazard posed by the waste and the dilution factor of its aqueous extract required to eliminate harmful effects on aquatic organisms (hydration). The overall hazard level of a particular type of waste is determined by the cumulative hazard of its individual components.

Fibrous and polymeric waste is categorized into preconsumer waste (generated during production processes such as cutting, spinning, weaving, and dyeing) and postconsumer waste (after use by consumers). Only materials that have not been in contact with biological fluids are accepted for laboratory research. Waste of medical origin must comply with the Federal Requirements for Waste Management (section X) and strictly segregated and disinfected prior to use. Materials that do not meet these criteria are excluded from the laboratory work. Clear labeling and documentation are maintained for all accepted waste, and a "waste acceptance checklist" is completed before introduction into research procedures. This ensures both the safety of students and compliance with regulatory standards.

According to this classification, the fibrous and polymer waste being studied in the development of efficient recycling technologies belongs to the class of low-hazard or practically nonhazardous materials, especially when considering the waste of textile materials derived from natural polymers such as cellulose, wool, or silk. Waste based on synthetic and semisynthetic polymers is considered moderately hazardous,

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Figure 1. Examples of different types of silk waste: cocoon waste (a), silk waste after reeling (b), and waste silk textile materials (c).

and if highly hazardous chemicals were used in their initial processing or finishing stage (such as dyeing or imparting special properties), they may pose a greater risk to ecological systems and also to the researchers directly in contact with them.

Additionally, the origin of fibrous waste coming into the laboratory must also be considered. Fibrous waste is classified into preconsumer waste (arising at production facilities during material manufacturing—cuttings, selvages, fiber or yarn breakage, etc.) and postconsumer waste (after consumer use). The latter can contain bacterial contamination, among other things, depending on how the material was used and stored after use. Naturally derived fibrous waste can serve as a nutrient medium for the development of pathogenic microorganisms and molds in environments of elevated humidity and temperatures favorable to bacterial life; polyethylene terephthalate (PET) bottles and many other items can also be included in this risk category.[39] Therefore, implementing disinfection procedures for waste materials before research is extremely important. This is especially important if the fibrous waste is of medical origin, with requirements defined in the Federal Requirements for Waste Management (Section X).[40] In the professional opinion of the authors, only fibrous materials and packaging waste that have lost their consumer properties and have not been in contact with patients' biological fluids, as defined as epidemiologically safe Class A waste, similar in composition to municipal solid waste, should be subject to study. Nevertheless, disinfection of all waste prior to work is mandatory.[41−43] Disinfection and decontamination procedures must be carried out under specialized conditions in order to avoid uncontrolled exposure of researchers to microorganisms or molds, in accordance with regulations.[31,44,45] These regulations specify occupational safety requirements for work involving chemicals, dry cleaning, washing, decontamination, and deactivation connected with plastic processing and handling of hazardous substances. Disinfection covers not only the waste under study but also all objects in the external environment that might be contaminated (benches, equipment, hands, air, water, etc.). Waste and glassware before research and after experiments are immersed in disinfectants; surfaces of laboratory benches and equipment are wiped with a brush or sprayed .

To carry out disinfection in the laboratory, a stock of disinfectants is required that have official registration, are

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approved for disinfecting specific objects, and have appropriate documents (certificate of state registration, declaration of conformity, and instructions for use). Disinfectants used for this purpose must meet the following requirements:

- They have a broad spectrum of activity against all types of microorganisms, including bacteria, viruses, and fungi;
- They can be used for disinfection by any method (wiping, spraying, and immersion);
- They possess the necessary physicochemical properties (rapid water solubility and cleaning action).

To reliably destroy microorganisms, it is important to observe standard requirements, including consumption rate, concentration, and exposure time. Effective disinfectants include cationic surfactants (quaternary ammonium salts), oxygen- and chlorine-containing products, tertiary amines, and guanidine derivatives, all effective against both Gram-negative and Gram-positive bacteria. Previously commonly used agents based on aldehydes and phenols are not permitted due to their high toxicity and danger. Laboratory practice shows that disinfectants with only static (growth-inhibiting but not microbe-killing) effects are of little use, as express tests will reveal bacteria some time after disinfection.

■ SILK, COTTON, AND PET WASTE RECYCLING AS A MODEL FOR SAFE LABORATORY-BASED STUDENT RESEARCH

Graduate students' research projects at the Department of Chemical Technologies at SPbSUTD are focused on the development of methods for recycling *Bombyx mori* natural silk waste into film materials through dissolution processes. *B. mori* silk waste is generated during various stages, such as harvesting (damaged or unreelable cocoons) and all stages of processing, including reeling, spinning, weaving, dyeing, and finishing. The total amount of waste generated across all sectors of the silk industry can reach 55%, with the degree of utilization of this valuable resource being relatively low and dependent on the fiber length in the waste.[11] Recycling expired silk products is also highly relevant. Examples of different types of waste are listed in Figure 1.

The aim of the graduate research is to obtain silk fibroin solutions and further fiber-film materials (shells for microcapsules in combination with chitosan, nonwoven materials by electrospinning, and auxiliary textile agents for improving the properties of other fibers). As mentioned, the first stage of the study is disinfection, e.g., decontamination and cleaning of waste from contaminants: fats and waxes, dyed nonprotein compounds, dust, and mineral oils. Proteinaceous substances, including sweat gland secretions, are often found in used textiles. Silk, due to its highly crystalline structure, is minimally susceptible to bacterial growth; nevertheless, storage conditions of the waste (temperature and humidity) and the protein nature of the fiber mean that aerobic proteolytic bacteria may be present. Therefore, the students undertake multistage cleaning of the supplied waste:

- Washing in a disinfectant solution based on a quaternary ammonium salt (0.5−1%);
- Washing for at least 30 min by boiling in an aqueous sodium bicarbonate solution (0.02 M);
- Decolorizing colored waste with a hydrogen peroxide solution (5 g of 3% hydrogen peroxide with 1 g of ammonia per liter of water for 30 min), followed by rinsing with clean water.

Risks associated with the cleaning process involve exposure to chemicals in solution and possible contact with bacteria on the surface of the waste. Most of the works are conducted in fume cupboards. As additional safety controls, researchers are required to always use personal protective equipment (lab coat, mask, goggles, and gloves), which significantly reduces the risk of bacteria reaching the skin, mucous membranes, and respiratory tract. The work is carried out under the direct supervision of a specially trained staff member. As a result, the combined action of the disinfectant solution, the high temperature during treatment with sodium bicarbonate, and hydrogen peroxide promotes the removal of contaminants from the silk waste and the destruction of bacteria. The completeness of disinfection is monitored according to regulatory recommendations[46] using express tests with catalase and fluorochrome indicators. The catalase express test for detecting bacterial contamination of abiotic surfaces, including in the form of biofilms, is based on the reaction of a hydrogen peroxide indicator with the catalase enzyme of the bacterial antioxidant defense system. The catalase indicator is applied by spraying onto the surface of the cleaned waste. If no microbubbles form on the surface of the fibrous material within 30 s as a result of hydrogen peroxide decomposition, this indicates the absence of catalase-positive bacteria, including in biofilm form. The result is confirmed by another independent test. An indicator with the fluorochrome dye Nile Red is applied to the tested surface by spraying, and a subsequent visualization of bacterial biofilms is performed using special protective glasses with a red-orange filter under green flashlight illumination. The absence of surface fluorescence indicates that there is no bacterial contamination of the surface. For reliable test results, it is important that the culture media meet the established operational criteria: microbial contamination should not exceed 10^3 colony-forming units (CFU) per cubic centimeter and preferably be below 10^2 CFU/cm^3. The water conductivity should not exceed 25 μS/cm (equivalent to a resistivity >0.4 MΩ·cm) and preferably be below 5 μS/cm at a temperature of 25 °C.

After disinfection and cleaning of the silk waste, students ground it up and dissolve it in a water−calcium chloride−ethanol (8:1:2 v/v) mixture at 50−55 °C and dialyze it through a semipermeable membrane M-Cel with a pore size of 14 kDa, with distilled water replaced five times, followed by filtration using a vacuum pump, Büchner funnel, and Büchner flask. The prepared solutions are used to produce films by casting onto a glass surface and removing the solvent through drying and fibers and nonwoven materials via electrospinning (22 G needle, distance from needle to collector 15 cm, voltage 20 kV, solution feed rate 1.0 mL/h, collector rotation speed 200 rpm, humidity 65%, room temperature 23 °C). Additionally, such fibroin-containing solutions may be reused for microencapsulation of various substances in a semipermeable shell made from a fibroin−chitosan mixture. For microencapsulation of a water-soluble biologically active substance, it is required to mix 5% fibroin and chitosan solutions and add an equal amount of liquid paraffin and Span-80 (1% of the total mixture mass). Stirring for 30 min, the cross-linking agent glutaraldehyde is added to the resulting emulsion, and the obtained microcapsules are washed and dried in a vacuum oven.

In addition to ensuring material purity, solvent-based cleaning poses fire, inhalation, and environmental risks. All work with flammable solvents is conducted in fume cupboards under functioning local exhaust ventilation (LEV) systems

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a) b)

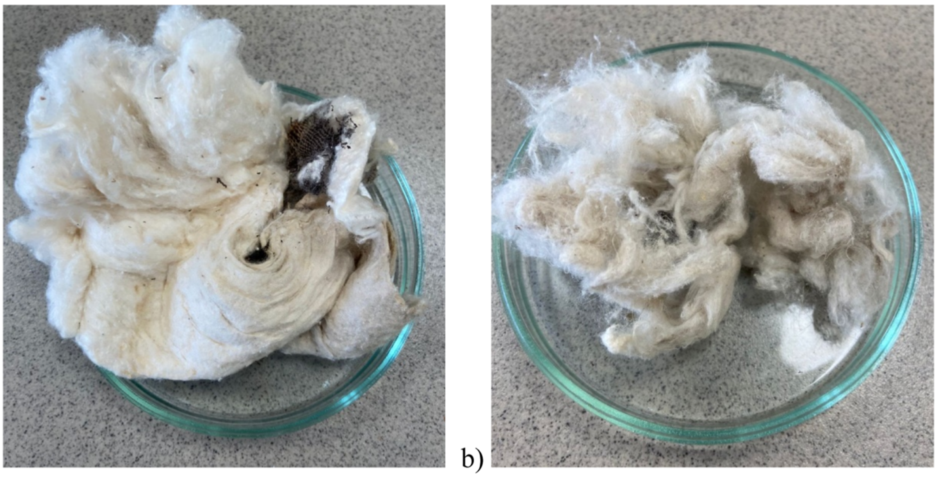

Figure 2. Examples of cotton waste used in student research: cotton carding waste (a) and cotton spinning waste (b).

with an air velocity of at least 15 m/s for enclosed procedures. Storage of solvents follows fire safety regulations, with flammable liquids kept in certified fire cabinets away from heat sources and student traffic areas. Spill kits and fire extinguishers are readily available, and students are trained in emergency response procedures. Where feasible, substitution with aqueous or less hazardous solvents is encouraged to reduce the environmental impact and chemical exposure. Waste solvents are collected in labeled containers and disposed of according to federal and university hazardous waste regulations. Regular audits from technical staff and dedicated safety personnel ensure compliance with ventilation, storage, and disposal requirements.

The chemical risks of these technologies are minimal, provided that the workspace is properly organized, as various equipment is required for vacuum filtration, fiber formation in laboratory setups, or electrospinning apparatus operation. Strict monitoring of the use of engineering controls and personal protective equipment is mandatory.

In laboratory conditions, depending on the amount, waste can be treated in heat-resistant flasks or laboratory drum-type chemical cleaning devices under LEV, avoiding manual filling of disinfectant solutions into the machines. If the disinfectant contains chlorine, the acidity of the medium must be monitored, as in an acidic environment with water, the solvent produces hydrochloric acid, which can destroy machine components and cause harm to the researcher's health. Using neutralizing agents as recommended by the equipment manufacturer is a good way to prevent corrosion and prolong the machine service life.

In practice, another important feature of research work on the chemical processing of fibrous waste is the potential formation of dust emissions and fiber debris aerosols. Such emissions can occur during sorting, grinding, and other preparatory steps for decontaminated waste. For any dust-producing waste, the laboratory should be equipped with the capturing hood and extraction enclosures with sleeve or bag filters. For example, student researchers at the Tashkent Institute of Textile and Light Industry are working on recycling cotton waste, including unrecoverable spinning waste, which is dust-like in structure due to repeated mechanical impacts at different stages of the technological process (see Figure 2).

Fine dust particles penetrate the respiratory tract and can lead to inflammation, chronic lung diseases, bronchitis, and asthma, as well as allergic reactions. Therefore, waste preparation for research should, as far as possible, be carried out under LEV. Tasks that can be performed in an enclosure (such as sorting, weighing, etc.) are recommended to be done inside fume cupboards/specialized ventilated enclosures providing an air velocity of at least 15 and 2.5 m/s in open openings. The dust concentration in the air is monitored by the gravimetric method and, when working with cotton waste, must not exceed 0.05 mg/m^3.

Cotton dust, depending on its source, may vary in particle size, according to the stage of production from which it originates. For example, during cotton cleaning, sliver drafting, and yarn formation, dust particles measure 1−3 μm; at the intensive mixing stage, 3−10 μm; during loosening, 10−20 μm; when unpacking bales, 20−40 μm; and during sliver drafting, 40−60 μm or more. Where this is not practical, it is mandatory to use respiratory protective equipment, goggles, and lab coats/coveralls to prevent contact with, and inhalation of, dust. The academic and technical staff supervise the correct storage and use of PPE and draw students' attention to the necessity of personal hygiene (washing hands and changing clothes to prevent the transfer of dust). Washing cotton or steaming it in an autoclave can help reduce dust generation. Following these measures helps to mitigate the risks associated with working in high-dust environments and to ensure student safety.

In laboratory research, to study the fundamental patterns of processes, it is often necessary to remove not only possible microorganisms but also impurities that the textile material inevitably acquires during manufacturing processes (such as finishing oils, light stabilizers, plasticizers, dyes, dispersants, dye intensifiers, leveling agents, thickeners, binders, agents for hydrophobic, crease-resistant, flame-retardant, or soil-repellent treatments, and others). A Soxhlet extraction apparatus is used for removing such accompanying substances, and the most effective solvent or mixture of solvents is selected depending on the chemical nature of possible impurities. This treatment is quite laborious and time-consuming but leads to a material that retains its original properties. In most cases, flammable hydrocarbon or oxygen-containing solvents are used in the Soxhlet apparatus, so this stage requires increased care from researchers and adherence to fire safety regulations.

An example is the stage of washing shredded PET waste (Figure 3) from pigments and adhesives in a Soxhlet apparatus

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Figure 3. Examples of shredded polyethylene terephthalate (PET) waste from plastic bottles (a) and textiles (b).

using a hydrocarbon solvent. This process makes it possible to obtain a polymer that is as free from impurities as possible, which is necessary for developing the scientific basis of the process. Students set this process up in fume cupboards under strict supervision. However, this stage is omitted in non-research applications, such as a large-scale PET waste recycling plant, where the treatment is generally limited to aqueous solutions of sodium hydroxide or surfactants.[47]

Several years of practice have shown that conducting experimental research on the development of recycling processes for fibrous and polymer waste in a student chemical laboratory must be preceded by a mandatory theoretical study of the physicochemical properties and the specific origin of the particular waste being handled, along with a comprehensive characterization of its toxicity, environmental, and bacterial hazards. In their research reports, the students are expected to provide concrete information about the potential risks associated with handling each particular type of waste (hazardous chemicals, technological and bacterial contamination, fire hazards, etc.) and discuss with their supervisor possible measures for minimizing these risks. The main drawback in organizing these studies has been students' lack of awareness regarding the risks associated with working with waste. Therefore, ensuring that students are as fully informed as possible, as well as maintaining quality control over the implementation of laboratory engineering controls, disinfection, and cleaning of waste before testing, is the key to the successful and safe execution of the research. Students typically learn about the associated hazards through a combination of formal training, written guidelines, and supervised laboratory practice. Supervision is typically ensured by laboratory staff, and students are rarely allowed to work entirely independently, especially at the start of their research. Laboratory waste and residues are collected by laboratory technical personnel, though students may assist in sorting or handling under close supervision. As with all novel research, students in Russian and Uzbekistani universities rely on information cascaded from their supervisors and laboratory assistants, as well as guidance found in methodological manuals, national laboratory regulations, local standard procedures and scientific journals. Compared with the UK, US, and many other universities, where centralized Environmental Health and Safety (EH&S) departments provide comprehensive training, conduct risk assessments, and are deeply involved in the research and teaching, Russian and Uzbekistani universities rely heavily on direct supervisor instruction and adherence to national regulations, with less integration of institution-wide H&S frameworks. This places greater responsibility on students and staff to educate themselves about potential hazards, safe handling procedures, and best practices in their research projects, while also fostering peer review and mutual monitoring.

■ CONCLUSIONS

Research into recycling technologies for textile industry waste and fiber-forming polymers plays a crucial role in advancing both the educational and research missions of universities. Such work must be carried out in chemical laboratories with strict adherence to general chemical safety protocols, fire safety regulations, and well-organized disinfection procedures and chemical protocols performed by trained personnel.

When these standards are upheld, laboratory-based research becomes highly effective, offering student researchers valuable practical experience while addressing the pressing challenge of developing and implementing efficient recycling methods for fibrous and polymer waste.

Importantly, all research should be grounded in the principle of hazard elimination, with particular emphasis on identifying and applying safer alternatives. In this regard, enzymatic methods for the chemical recycling of fibrous waste represent a promising avenue. These approaches not only enhance the efficiency of material preparation for secondary processing but also significantly improve the safety profile of laboratory operations.

While the proposed approach ensures safe and effective student engagement in recycling research, several limitations remain. Resource constraints, including the availability of fume cupboards, LEV systems, and specialized disinfection equipment, may limit the scale of experiments. Variability in student experience and prior laboratory training can affect adherence to protocols, requiring additional supervision and instruction. Instrumentation constraints, including limited access to the Soxhlet apparatus, filtration units, or electrospinning setups, may restrict the range of experimental procedures. Finally, some chemical hazards and microbiological risks inherent to fibrous and polymeric waste cannot be fully eliminated, underscoring the need for continuous monitoring and ongoing training.

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Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript. CRediT: **Elena Sashina** conceptualization, resources, writing - original draft; **Olga Kuzmina** conceptualization, writing - original draft, writing - review & editing; **Iroda Nabieva** conceptualization, writing - original draft.

Notes

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REFERENCES

(1) Blackburn, R. S. *Sustainable Textiles*; Woodhead Publishing Limited, 2009.

(2) Global Market Insighs. Textile Recycling Market Size—By Source, Technology, Material, Waste, End Use Analysis, Share, Growth Forecast, 2025−2034, 2024. https://www.gminsights.com/industry-analysis/textile-recycling-market (accessed July 30, 2025).

(3) Interfax. Putin Orders Drafting Ecology National Project. https://interfax.com/newsroom/top-stories/100939/#:~:text=At%20least%2050%20hazardous%20sites,relevant%20report%20by%20September%201. (accessed Aug 08, 2025).

(4) European Parliament. Fast Fashion: EU Laws for Sustainable Textile Consumption Topics. https://www.europarl.europa.eu/topics/en/article/20201208STO93327/fast-fashion-eu-laws-for-sustainable-textile-consumption#:~:text=Clothing%20waste%20in%20landfills%20and%20low%20recycling%20rates&text=Less%20than%20half%20of%20used,only%20now%20starting%20to%20emerge. (accessed Oct 12, 2025).

(5) European Environment Agency. Plastics Topics. https://www.eea.europa.eu/en/topics/in-depth/plastics#:~:text=Global%20consumption%20of%20plastic%20is,the%20environment%2C%20including%20the%20oceans. (accessed Oct 12, 2025).

(6) Government of the Russian Federation. *On the Approval of the Lists of Goods, Packaging, and Waste Subject to Recycling, and the Recycling Standards*: Russia, 2023.

(7) Alimova, D.; Nabieva, I.; Atakhanov, A. Paper production from the waste of medicinal plants. *E3S Web of Conferences*; EDP Sciences, 2023; Vol. *452*. 05013. .

(8) Khramchikhin, V.; Yakovleva, O. I.; Sashina, E. S. Copper-containing non-woven materials from silk waste. *IOP Conference Series: Earth and Environmental Science*; IOP Publishing Ltd, 2020; Vol. *613*, p 012054..

(9) Yakovleva, O. I.; Sashina, E. S.; Nabieva, I. A. Needle Punched Nonwoven Silk Waste Material with Antifungal Properties for Air Filtration. *J. Nat. Fibers* **2022**, *19* (17), 15367−15376.

(10) Yakovleva, O. I.; Sashina, E. S.; Osipov, M. I.; Smirnov, G. P. Non-Woven Needle Punched Material with Silver Nanoparticles from Natural Silk Fiber Waste. *Fibre Chem.* **2020**, *52* (4), 263−268.

(11) Sashina, E. S.; Yakovleva, O. I. The Current State and Prospects of Recycling Silk Industry Waste into Nonwoven Materials. *Fibers* **2023**, *11* (6), 56−69.

(12) Morales Méndez, G.; del Cerro Pérez, A.; del Cerro Velázquez, F. Prototype Pultrusion of Recycled Polyethylene Terephthalate Plastic Bottles into Filament for 3D Eco-Printing: Education for a Sustainable Development Project. *Sustainability* **2024**, *16* (19), 8347−8359.

(13) Mikhailovskaya, A. P.; Kichaeva, Ya. A.; Elokhin, I. V.; Kuz'menko, A. A. Catalytic Hydrolysis of Polyester Fiber Using Quaternary Ammonium Salts. *Fibre Chem.* **2025**, *56* (6), 367−371.

(14) Dogu, O.; Pelucchi, M.; Van de Vijver, R.; Van Steenberge, P. H. M.; D'hooge, D. R.; Cuoci, A.; Mehl, M.; Frassoldati, A.; Faravelli, T.; Van Geem, K. M. The Chemistry of Chemical Recycling of Solid Plastic Waste via Pyrolysis and Gasification: State-of-the-Art, Challenges, and Future Directions. *Prog. Energy Combust. Sci.* **2021**, *84*, 100901.

(15) Schade, A.; Melzer, M.; Zimmermann, S.; Schwarz, T.; Stoewe, K.; Kuhn, H. Plastic Waste Recycling−A Chemical Recycling Perspective. *ACS Sustain. Chem. Eng.* **2024**, *12* (33), 12270−12288.

(16) Hebei Weihigh Technology Co., Ltd. Application of Regenerated Polyester Fiber in Filling. https://www.weihighpsf.com/news/application-of-regenerated-polyester-fiber-in-filling/ (accessed July 30, 2025).

(17) Jia, X.; Qin, C.; Friedberger, T.; Guan, Z.; Huang, Z. Efficient and Selective Degradation of Polyethylenes into Liquid Fuels and Waxes under Mild Conditions. *Sci. Adv.* **2016**, *2* (6), 1−7.

(18) Pereira, P.; Slear, W.; Testa, A.; Reasons, K.; Guirguis, P.; Savage, P. E.; Pester, C. W. Fast Hydrolysis for Chemical Recycling of Polyethylene Terephthalate (PET). *RSC Sustain.* **2024**, *2* (5), 1508−1514.

(19) Zheng, M.; Zhu, X.; Li, Y.; Zhang, Q.; Dong, W.; Wang, W. Prochiral Selectivity in Enzymatic Polyethylene Terephthalate Depolymerization Revealed by Computational Modeling. *ACS ES&T Eng.* **2024**, *4* (9), 2306−2316.

(20) Ghosh, J.; Repon, M. R.; Rupanty, N. S.; Asif, T. R.; Tamjid, M. I.; Reukov, V. Chemical Valorization of Textile Waste: Advancing Sustainable Recycling for a Circular Economy. *ACS Omega* **2025**, *10* (12), 11697−11722.

(21) Zheng, J.; Arifuzzaman, M.; Tang, X.; Chen, X. C.; Saito, T. Recent Development of End-of-Life Strategies for Plastic in Industry and Academia: Bridging Their Gap for Future Deployment. *Mater. Horiz.* **2023**, *10* (5), 1608−1624.

(22) Kuzmina, O.; Jankowski, S.; Fabiańska, A.; Sashina, E.; Wawro, D. Preswelling of Cellulose Pulp for Dissolution Inionic Liquid. *Cellul. Chem. Technol.* **2014**, *48* (1−2), 45−51.

(23) Sashina, E. S.; Kashirskii, D. A. Pyridinium-Based Ionic Liquids — Application for Cellulose Processing. In *Ionic Liquids—Current State of the Art*; Handy, S., Ed.; InTech, 2015; pp 389−417..

(24) Sashina, E. S.; Golubikhin, A. Yu.; Susanin, A. I. Prospects for Producing New Biomaterials Based on Fibroin. *Fibre Chem.* **2015**, *47* (4), 253−259.

(25) Susanin, A. I.; Sashina, E. S.; Ziółkowski, P.; Zakharov, V. V.; Zaborski, M.; Dziubiński, M.; Owczarz, P. A Comparative Study of Solutions of Silk Fibroin in 1-Butyl-3-Methylimidazolium Chloride and Acetate. *Russ. J. Appl. Chem.* **2018**, *91* (4), 647−652.

(26) Ghosh, J.; Rupanty, N. S.; Asif, T. R.; Noor, T.; Islam, T.; Reukov, V. Advancing Biomedical Applications: Integrating Textile Innovations with Tissue Engineering. *Biomed. Mater.* **2025**, *20* (4), 042002−0420041.

(27) Eom, Y.; Kim, B. C. Solubility Parameter-Based Analysis of Polyacrylonitrile Solutions in N,N-Dimethyl Formamide and Dimethyl Sulfoxide. *Polymer* **2014**, *55* (10), 2570−2577.

(28) Shahid, M. A.; Hossain, M. T.; Habib, M. A.; Islam, S.; Sharna, K.; Hossain, I.; Mortuza Limon, M. G. Prospects and Challenges of Recycling and Reusing Post-Consumer Garments: A Review. *Clean Eng. Technol.* **2024**, *19*, 100744.
(29) Government of the Russian Federation. *On the Approval of the Fire Safety Regulations in the Russian Federation*: Russia, 2020.
(30) Ministry of Natural Resources of the Russian Federation. *Safety Regulations for Work in Analytical Laboratories (General Provisions). Methodological Guidelines*: Russia, 2003.
(31) Ministry of Labour of the Russian Federation. *Occupational Safety Requirements for the Use of Chemical Substances in Laboratories (Registered by the Ministry of Justice of Russia on 22 December 2020 No. 61680)*: Russia, 2020.
(32) United Nations Environment Programme (UNEP). Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal, 1989. https://www.basel.int/ (accessed July 30, 2025).
(33) Lallas, P. L. The Stockholm Convention on Persistent Organic Pollutants. *Am. J. Int. Law* **2001**, *95* (3), 692−708.
(34) United Nations Environment Programme (UNEP). Montreal Protocol on Substances That Deplete the Ozone Layer, 1987. https://ozone.unep.org/treaties/montreal-protocol (accessed July 30, 2025).
(35) United Nations Environment Programme (UNEP). Strategic Approach to International Chemicals Management (SAICM), 2006. https://www.saicm.org/ (accessed July 30, 2025).
(36) Hoeneveld, D. Chapter 3: The EU and Safety Management in Higher Education. In *Challenges for Health and Safety in Higher Education and Research Organisations*; Kuzmina, O., Hoyle, S., Eds.; Royal Society of Chemistry: London, 2020; pp 46−69.
(37) Fatemi, F.; Dehdashti, A.; Jannati, M. Implementation of Chemical Health, Safety, and Environmental Risk Assessment in Laboratories: A Case-Series Study. *Front. Public Health* **2022**, *10*, 1−9.
(38) Ministry of Natural Resources of the Russian Federation. *On the Approval of Criteria for Classifying Waste into Hazard Classes I−V According to their Environmental Impact*: Russia, 2025.
(39) Dhaka, V.; Singh, S.; Anil, A. G.; Sunil Kumar Naik, T. S.; Garg, S.; Samuel, J.; Kumar, M.; Ramamurthy, P. C.; Singh, J. Occurrence, Toxicity and Remediation of Polyethylene Terephthalate Plastics. A Review. *Environ. Chem. Lett.* **2022**, *20* (3), 1777−1800.
(40) Federal Service for Surveillance on Consumer Rights Protection and Human Wellbeing (Rospotrebnadzor). *Requirements for Waste Management (Section X), SanPiN 2.1.3684−21*: Russia, 2021.
(41) Federal Service for Surveillance on Consumer Rights Protection and Human Wellbeing (Rospotrebnadzor). *On the Disposal of Class A Medical Waste*: Russia, 2021.
(42) Chief State Sanitary Doctor of the Russian Federation. *On the Approval of Sanitary Rules and Norms SanPiN 3.3686−21 (as Amended on 25 May 2022)*: Russia, 2021.
(43) Chief State Sanitary Doctor of the Russian Federation. *Sanitary and Epidemiological Requirements for the Prevention of Infectious Diseases (SanPiN 3.3686−21)*: Russia, 2021.
(44) Chief State Sanitary Doctor of the Russian Federation. *Organisation and Implementation of Disinfection Activities at Various Facilities During the Preparation and Conduct of Mass Events*: Russia, 2013.
(45) Chief State Sanitary Doctor of the Russian Federation. *On the Enactment of Sanitary and Epidemiological Rules SP 3.5.1378−03 'Requirements for Carrying out Disinfection*: Russia, 2003.
(46) Federal Service for Surveillance on Consumer Rights Protection and Human Wellbeing (Rospotrebnadzor). *Methods for Detecting Microbial Biofilms on Abiotic Surfaces: Methodological Guidelines*: Russia, 2020.
(47) Federal Agency for Technical Regulation and Metrology (Rosstandart). *Resource Conservation. Waste Management. Characteristics of Recycled Polyethylene Terephthalates*: Russia, 2016.

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ACS Chem. Health Saf. 2025, 32, 801−809