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RESEARCH OF WASTE PAPER CLEANING METHODS: CHEMICAL REAGENTS AND THEIR IMPACT ON THE QUALITY OF RECYCLING

Annotation: *One of the problems of the paper industry is the search for raw materials. Due to the depletion of non-renewable resources, the role of recycling waste paper, which makes up about 7% of solid municipal waste and contains valuable cellulose, is growing. In developed countries, millions of tons of paper packaging are produced annually, creating large volumes of waste paper [1].*

Paper recycling plays a significant role in reducing environmental impacts, reducing waste volumes and minimizing the use of primary resources. However, despite advances in paper recycling, the problem of cleaning up contaminants such as chemicals, paints and pigments remains relevant. These contaminants reduce the quality of recycled material and increase the complexity of the production process. This article reviews modern paper cleaning methods such as the use of surfactants, chemical reagents and combined approaches to improve recycling efficiency. In this study, a set of chemical reagents including sodium dodecyl sulfate (SDS) and sodium hypochlorite were selected to evaluate their impact on paper cleaning. To evaluate the efficiency of waste paper cleaning, physicochemical methods including UV spectroscopy, IR spectroscopy, thermogravimetric analysis and differential thermal analysis were used, which provided comprehensive information on the composition and changes in the material during processing.

Key words: *Waste paper, chemical cleaning, cellulose, surfactants, alkali.*

Introduction

Waste paper is secondary raw material containing significant amounts of cellulose, a polysaccharide that gives it high durability and structural strength. This makes waste paper a valuable material for reuse in various applications [2]. In 2022, global consumption of paper products exceeded 414 million tones, of which about 60% is recycled, making waste paper an affordable and cost-effective raw material [3]. It is most often recycled to produce new paper [4]. However, due to its high cellulose content, waste paper has the potential to be used as a road surface stabilizer and sorbent, opening up opportunities for its recycling in various chemical processes and industries.

Waste paper is an important resource for recycling, but its efficient use requires preliminary cleaning from contaminants. Previous studies [5] have shown that paper and paper products can contain significant amounts of chemicals. Most of these substances are associated with the printing industry, where, for example, more than 7,000 chemicals are used in the production of inks for food packaging [6]. These substances, including synthetic dyes, can significantly contaminate waste paper, reducing its quality and increasing the complexity of recycling.

Therefore, one of the key stages in waste paper recycling is deinking [7]. The main purpose of deinking is to obtain pulp of the desired whiteness and without visible to the naked eye paint stains. This process requires the complete removal of pigment particles larger than 40 microns from the pulp. To improve the optical properties of paper, such as whiteness or brightness, it is also necessary to remove smaller pigment particles [8]. This improves the visual quality of the recycled material and allows it to be used in the production of high-quality paper.

The most common traditional method of ink removal is the flotation process, which is widely used in the paper industry to extract contaminants such as toner. This method involves the use of surfactants, which significantly increase the efficiency of the flotation process, and requires high temperatures to accelerate the aggregation of toner particles [9]. Surfactants not only facilitate the separation of ink from fibers, but also significantly accelerate the cleaning process, making flotation an effective and cost-effective method widely used in paper recycling. Although the flotation process also uses bleaching chemicals, which increase the load on environmental systems, their use remains justified in terms of efficiency and reduction of recycling costs.

In recent years, the spherical agglomeration method has been proposed as an important complement to traditional processes [10]. This method uses a dispersion of hydrophobic particles such as polyethylene or wax-plasticized materials to effectively collect ink particles in the pulp suspension. This approach has been found to be more efficient than conventional flotation due to improved pulp consistency and lower fiber loss [11]. An important aspect is the control over the size and surface chemistry of the plastic beads, which significantly improves the removal efficiency of contaminants such as soot and ink. Plastic beads coated with silicone or paraffin oil have been shown to be effective in removing ink from water [12].

Another promising approach is ink removal via adsorption, which offers high efficiency with notably low energy and water consumption. One example involves suspensions of newsprint and magazine paper, from which ink is extracted using polymer particles such as polyamide (PA) [13]. Compared to traditional flotation, this method operates at higher solids content, enabling up to 90% savings in water and energy use. This development opens new avenues for sustainable and cost-effective practices in the paper recycling industry.

Growing concern for environmental sustainability has spurred interest in alternative ink removal techniques, notably enzymatic methods [7]. These technologies offer clear ecological advantages, such as reduced pollution risks and lower toxicity of wastewater [14]. Despite their benefits, enzymatic approaches remain less economically viable due to the high cost of enzyme preparations [15]. In addition, such methods have yet to match the scalability and accessibility of conventional chemical deinking processes.

In this regard, the purpose of this work is to analyze the effectiveness of various chemical methods of paper cleaning in the process of recycling waste paper. Particular attention will be paid to the selection of optimal reagents that will ensure high quality of the recycled material, effectively removing contaminants and increasing the whiteness of the paper.

Materials and methods

Materials

The object of the study was office waste paper containing paints and inks (Figure 1).

Figure 1 – Sample of office waste paper

For effective cleaning, it is important to select suitable surfactants and chemical reagents that remove contaminants without damaging the cellulose structure of the paper.

In this study, the following methods were used to clean waste paper:

1. A method based on the use of specialized chemicals that effectively remove ink and other organic contaminants, which allows the contaminant particles to be dispersed and facilitated their removal.
2. A bleaching method aimed at improving the whiteness of recycled paper, which helps restore its original optical properties, as well as reduce the color indicators to the level of virgin raw materials.
3. A combined method that uses both of the previous approaches, which allows for a synergistic effect to be achieved in the cleaning process, improving both the removal of contaminants and increasing the whiteness of the paper.

Chemical reagents used for cleaning and bleaching waste paper:

1. Sodium dodecyl sulfate (SDS) as a surfactant, due to its high efficiency in removing ink, as shown in studies [16], where SDS is successfully used to disperse ink particles.
2. Sodium hypochlorite (NaClO), the choice of which is justified by its effectiveness in increasing the whiteness of paper, according to a study [16], where the use of a 5-10% NaClO solution reduces the color properties of paper to the level of primary raw materials.
3. Combined use of surfactants and sodium hypochlorite.

Methodology for cleaning waste paper using chemical reagents

Preparation of waste paper

Before processing, the waste paper was crushed and soaked in distilled water for 24 hours to ensure uniform distribution of the reagents throughout the entire mass of the material (Figure 2).

Figure 2 – Waste paper prepared for cleaning

Method of removing pollutants using surfactants and sodium hypochlorite

After preparation, the waste paper was divided into three parts for treatment with different chemical reagents.

The first part of the waste paper was treated with a surfactant solution (100 mg SDS dissolved in 200 ml water) with constant stirring for 4 hours at room temperature. After that, the fibers were washed with a large amount of water to remove surfactant residues and were pressed and dried at room temperature (Figure 3).

Figure 3 – Fragment of waste paper after surfactant cleaning

The second part of the waste paper was chemically cleaned using sodium hypochlorite ($NaClO$), which is used in the bleaching stage to decompose dark organic contaminants. The $NaClO$ solution (33.7 ml per 300 ml of water) was used for 2 hours, after which the waste paper was washed to remove chlorine-containing compounds (Figure 4).

Figure 4 – Waste paper after treatment with sodium hypochlorite

Method of combined cleaning of waste paper

The third part of the waste paper was subjected to a combined treatment using both surfactants and sodium hypochlorite. The waste paper was first treated with surfactants to remove ink and contaminants, and then with sodium hypochlorite to increase whiteness. The cleaned samples are shown in Figure 5.

Figure 5 – Waste paper after combined cleaning

Study of the efficiency of waste paper cleaning

UV spectroscopy was used to detect organic contaminants such as ink residues that absorb ultraviolet light. This allowed us to evaluate how effectively the reagents remove contaminants. Absorption spectra were measured using a UV2600I UV-VIS spectrophotometer (Shimadzu, Japan).

Fourier transform infrared spectroscopy in ATR mode was used to study changes in the chemical composition of waste paper and cellulose fibres after processing. This method revealed changes in the functional groups of cellulose and other contaminants (e.g. pigments and chemical additives), which made it possible to assess the degree of contaminant removal and the effect on the paper structure. The studies were carried out using an ALPHA II analytical instrument in the range from 500 to 4000 cm $^{-1}$.

To assess the thermal stability and decomposition mechanism of the waste paper samples under study, a comprehensive thermal analysis was performed, including thermogravimetric and differential thermal analysis studies. The studies were conducted on a NETZSCH STA 409 device at a temperature of 10-700 °C in a nitrogen atmosphere with a heating rate of 10 K/min.

Results and their discussion

In this study, the selection of chemical reagents for cleaning waste paper from contaminants was based on the results of previous studies, as well as their industrial applicability and efficiency. In the study [17], it was found that the efficiency of cleaning packaging waste directly depends on the type of surfactant (SAS) used and its concentration. This factor plays a key role in the processes of removing ink and other organic contaminants, such as pigments and adhesives, present in waste paper.

Sodium dodecyl sulfate (SDS) was chosen as the surfactant for this study due to its high efficiency in dispersing ink particles and other organic contaminants as shown in several studies [16]. SDS is one of the most widely used surfactants in industry as it has good detergency properties and can effectively break the bonds between ink and cellulose fibers, facilitating their removal from the pulp.

Sodium hypochlorite (NaClO) was selected as the bleaching agent. This choice is also supported by its widespread use in industrial paper production, where NaClO effectively removes dark organic contaminants and improves paper whiteness [18]. The strong oxidizing action of sodium hypochlorite allows for the effective removal of pigments and stubborn contaminants, making it indispensable in the waste paper bleaching process. The combined use of SDS and NaClO was chosen to maximize cleaning efficiency, ensuring both the removal of contaminant particles and the improvement of the optical characteristics of recycled paper.

UV spectroscopy was used to analyze the efficiency of paper cleaning from contaminants. The goal was to identify residual ink and other organic contaminants that absorb ultraviolet light and evaluate their removal after the use of various chemical reagents.

The UV spectrum of waste paper before processing (Figure 6) shows pronounced absorption peaks at wavelengths of 220 nm and 280 nm.

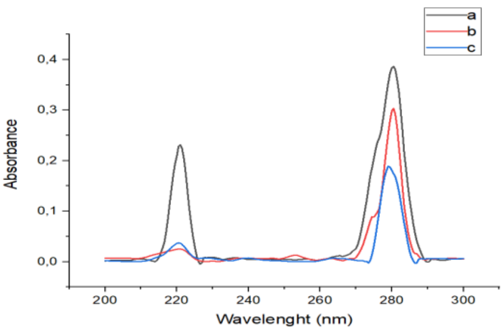

Figure 6 – UV spectrum of samples at a wavelength of 200-300 nm

a) surfactant; b) combined surfactant and sodium hypochlorite; c) sodium hypochlorite

The peak at 220 nm may be due to the presence of inorganic nitrogen-containing compounds such as nitrites and nitrates , which can strongly absorb UV radiation in the range of 200-226 nm due to n→π* electronic transitions. This is consistent with the data of Li et al. [19], where the absorption integral in this region was used to estimate the inorganic nitrogen content in aqueous extracts of organic waste.

Absorption at 280 nm indicates the presence of aromatic organic compounds, including phenols, benzoic acids, aniline derivatives, polyenes and polycyclic aromatic hydrocarbons. These compounds have a developed π-system, and their characteristic electron transition (π→π*) appears in the region of 270-280 nm. According to Martín et al. [20], the full aromaticity is recorded precisely in this spectral range, which makes the peak at 280 nm an indicator of aromatic contaminants such as ink and pigment residues.

After treating waste paper with a surfactant solution and sodium hypochlorite (Figure 6a, 6b), a decrease in the intensity of both peaks is observed, indicating the removal of part of both inorganic and organic pollutants. However, the presence of weakly expressed peaks indicates partial preservation of pollutants.

The greatest decrease in the intensity of the peaks at 220 nm and 280 nm is observed after combined treatment with surfactants and sodium hypochlorite (Figure 6c), indicating a synergistic effect of the reagents. The almost complete disappearance of the peak at 280 nm may indicate the destruction of aromatic fragments of pigments and inks, which is also confirmed by an increase in the whiteness of the paper and an improvement in its optical characteristics.

Since UV spectroscopy to a greater extent reflects changes associated with the presence and removal of organic contaminants, FTIR spectra were analyzed to obtain a more complete picture of the impact of reagents on waste paper, allowing one to assess possible structural changes in the cellulose matrix.

Analysis of the FTIR spectra of the purified waste paper samples shown in Figure 7 showed that the main chemical components of cellulose remain stable after treatment. This is confirmed by the fact that the characteristic absorption bands corresponding to the functional groups of cellulose have not undergone significant changes, indicating that the structure of the material has been preserved.

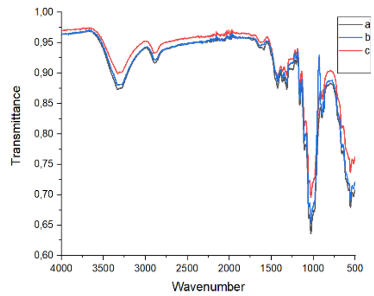

Figure 7 – IR spectrum of purified waste paper samples

a) surfactant; b) combined surfactant and sodium hypochlorite; c) sodium hypochlorite

Thus, a broad peak at about 3300 cm^{-1}, caused by the stretching of O–H bonds, indicates the presence of hydroxyl groups in the cellulose structure [21]. Its stability in both the original and processed waste paper confirms the preservation of hydrogen bonds and the absence of significant changes in the chemical composition [22].

The band around 2880 cm^{-1}, corresponding to C–H stretching vibrations , also remains unchanged after treatment, as do the peaks at 1310 cm^{-1} and 1163 cm^{-1} , associated with stretching of C–O bonds in the cellulose structure. Taken together, these observations indicate that cellulose molecules retain their basic structural characteristics even after exposure to chemical reagents.

Of interest is the peak at 930 cm^{-1} observed in Figure 7a, which is associated with C–H vibrations in aromatic groups. Its presence after surfactant treatment indicates partial retention of aromatic contaminants, such as pigments or residual organic matter. However, when using sodium hypochlorite (Figure 7b) and the combined method (Figure 7c), the intensity of this band decreases significantly, indicating more efficient removal of aromatic impurities and, accordingly, deeper cleaning of waste paper. Quantitative transmittance values of the FTIR spectra confirm the efficiency of various treatment methods. For the surfactant -treated sample, the transmittance was 0.82672; after sodium hypochlorite treatment – 0.85061; and in the case of the combined treatment – 0.89975. The increase in transmission value correlates with a decrease in the amount of organic pollutants, in particular aromatic compounds that absorb infrared radiation. At the same time, the stability of the main bands characteristic of cellulose confirms that the higher transparency is not associated with the destruction of the fiber, but is due to more effective purification from impurities.

To assess the thermal stability and decomposition nature of the samples under study, a comprehensive thermal analysis was performed, including thermogravimetric analysis (TGA) and differential thermal analysis (DTA). The results are shown in Figures 8 and 9.

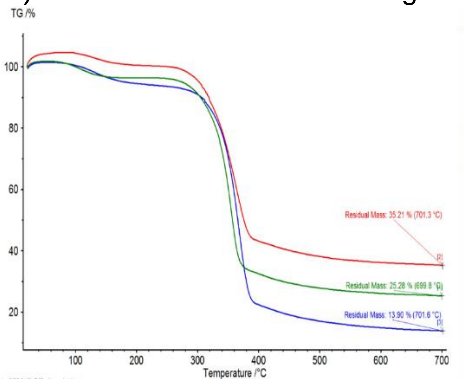

Figure 8 – Thermogravimetric analysis (TGA) curve of purified waste paper samples using various reagents

1) surfactant; 2) combined surfactant and sodium hypochlorite; 3) sodium hypochlorite

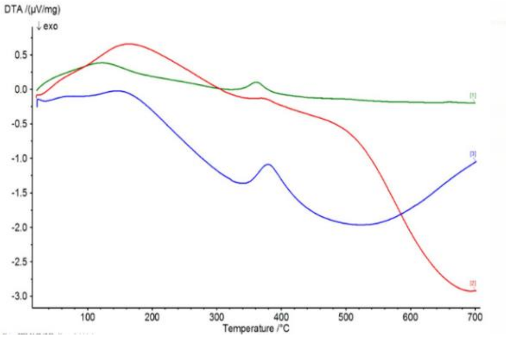

Figure 9 – Differential thermal analysis (DTA) curve of purified waste paper samples using different reagents

1) surfactant; 2) combined surfactant and sodium hypochlorite; 3) sodium hypochlorite

The thermogravimetric curves of all samples show a multistage mass loss (Figure 8). In the temperature range up to 150 °C, a slight decrease in mass (2-5%) is recorded, associated with the removal of physically bound moisture and volatile compounds. The main decomposition range (250-450 °C), according to the authors of a number of works [2 3, 24], corresponds to the thermal destruction of organic components, primarily cellulose, hemicellulose and lignin.

The residual weight of the samples at 700 °C varies significantly depending on the pre-treatment method. The original waste paper sample (Figure 8-1) treated with surfactant is characterized by a residue of 25.28%. The waste paper sample treated with sodium hypochlorite has a residual weight of 35.21%, which may indicate the formation of stable inorganic compounds. At the same time, the combined-treated sample (Figure 8-3) showed a minimum residue of -13.90%, indicating a more complete destruction of the organic matrix and the removal of impurities.

Differential thermal analysis confirmed the identified features (Figure 9). All curves show endothermic peaks in the region up to 150 °C, corresponding to the removal of moisture. The main exothermic peaks in the range of 350-450 °C are associated with the active phase of decomposition of organic components. A particularly intense exothermic effect is observed in the sample of purified waste paper using surfactants (Figure 9-1) and a combined method (Figure 9-2). The waste paper sample purified using sodium hypochlorite (Figure 9-3) demonstrates a smoother thermal effect, which may be due to the suppression of the reaction due to the high content of inorganic fragments, similar to that observed in [25, 26]. Combined modification promotes deeper degradation of the organic phase, a reduction in the residue, and an increase in the intensity of exothermic processes [23-27].

In general, the results of thermal analysis confirm the high efficiency of the proposed cleaning methods, which makes them promising for further use in industrial recycling of waste paper aimed at improving the quality and stability of the final product.

Conclusion

The study assessed the impact of various chemical reagents on the process of cleaning waste paper from pollutants. The main object of the study was surfactants and bleaching agents used to remove ink, pigments and other organic pollutants, as well as to increase the whiteness of recycled paper.

The use of sodium dodecyl sulfate (SDS) as a surfactant has shown high efficiency in removing organic contaminants due to its ability to break bonds between contaminants and cellulose. In combination with sodium hypochlorite (NaClO), even better results were achieved, since NaClO effectively removes persistent pigments and increases the whiteness of the paper.

The UV spectral analysis showed that the combined use of SDS and NaClO contributed to a significant reduction in the intensity of absorption peaks, indicating greater removal of both organic and inorganic contaminants. This was confirmed by the improvement in the optical characteristics of the recycled paper.

Based on infrared spectroscopy (FTIR), it was shown that the main components of the pulp remain stable after treatment, and the improvement in the transparency of waste paper after cleaning confirms the effectiveness of the selected reagents. Thermal analysis (TGA and DTA) showed that the combined treatment of waste paper using SDS and NaClO promotes a more complete removal of organic contaminants, which leads to a decrease in residual mass and an increase in exothermic processes, confirming the higher efficiency of this method.

Thus, the conducted studies have shown that the combined use of surfactants and sodium hypochlorite is an effective approach for cleaning waste paper, improving its quality, thermal stability and whiteness. This can significantly improve the efficiency of paper recycling processes and improve the environmental performance of recycled materials.

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МАКУЛАТУРАНЫ ТАЗАЛАУ ӘДІСТЕРІН ЗЕРТТЕУ: ХИМИЯЛЫҚ РЕАГЕНТТЕР ЖӘНЕ ОЛАРДЫҢ ҚАЙТА ӨҢДЕУ САПАСЫНА ӘСЕРІ

Қағаз өнеркәсібінің мәселелерінің бірі – шикізатты іздеу. Қалпына келмейтін ресурстардың таусылуына байланысты тұрмыстық қатты қалдықтардың шамамен 7%-ын құрайтын және құрамында бағалы целлюлоза бар макулатураны қайта өңдеудің рөлі артып келеді. Дамыған елдерде жыл сайын миллиондаған тонна қағаз қаптамалары шығарылады, бұл үлкен көлемдегі макулатураны құрайды [1].

Қағазды қайта өңдеу экологиялық жүктемені азайтуда, қалдықтарды азайтуда және бастапқы ресурстарды пайдалануды азайтуда маңызды рөл атқарады. Дегенмен, қағазды қайта өңдеудегі жетістіктерге қарамастан, химиялық заттар, бояулар және пигменттер сияқты ластаушы заттарды жою мәселесі өзекті болып қала береді. Бұл ластаушылар қайта өңделген материалдың сапасын төмендетеді және өндіріс процесінің күрделілігін арттырады. Бұл мақалада беттік белсенді заттарды, химиялық реагенттерді пайдалану және қайта өңдеу тиімділігін арттырудың аралас тәсілдері сияқты қағазды тазалаудың заманауи әдістері қаралады. Зерттеу барысында қағазды тазалауға әсерін бағалау үшін натрий додецил сульфаты (SDS) және натрий гипохлоритін қамтитын химиялық реагенттер жиынтығы таңдалды. Қағаз қалдықтарын тазалаудың тиімділігін бағалау үшін УК-спектроскопия, ИҚ-спектроскопия, термогравиметриялық талдау және дифференциалды термиялық талдауды қамтитын физика-химиялық әдістер қолданылды, осы әдістер кезінде материалдың құрамы мен өзгерістері туралы жан-жақты ақпарат алынды.

Түйін сөздер: *макулатура, химиялық тазалау, целлюлоза, беттік белсенді заттар, сілті.*

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ИССЛЕДОВАНИЕ МЕТОДОВ ОЧИСТКИ МАКУЛАТУРЫ: ХИМИЧЕСКИЕ РЕАГЕНТЫ И ИХ ВЛИЯНИЕ НА КАЧЕСТВО ПЕРЕРАБОТКИ

Одной из проблем бумажной промышленности является поиск сырья. Из-за истощения невозобновляемых ресурсов растет роль переработки макулатуры, которая составляет около 7% твердых бытовых отходов и содержит ценную целлюлозу. В развитых странах ежегодно производятся миллионы тонн бумажных упаковок, создавая большие объемы макулатуры [1].

Переработка бумаги играет значительную роль в снижении экологической нагрузки, сокращении объемов отходов и минимизации использования первичных ресурсов. Однако, несмотря на достижения в переработке макулатуры, проблема очистки от загрязнителей, таких как химические вещества, краски и пигменты, остаётся актуальной. Данные загрязнители снижают качество переработанного материала и увеличивают сложность производственного процесса. В данной статье рассматриваются современные методы очистки макулатуры, такие как использование поверхностно-активных веществ, химических реагентов и комбинированных подходов для улучшения эффективности переработки. В рамках исследования был выбран комплекс химических реагентов, включая додецилсульфат натрия (SDS) и гипохлорит натрия, для оценки их воздействия на очистку макулатуры. Для оценки эффективности очистки макулатуры использовались физико-химические методы, включая УФ-спектроскопию, ИК-спектроскопию, термогравиметрический анализ и дифференциальный термоанализ, что позволило получить всестороннюю информацию о составе и изменениях в материале в ходе обработки.

Ключевые слова: *Макулатура, химическая очистка, целлюлоза, поверхностно- активные вещества, щелочь.*

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