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APPROACHES TO ENSURING RESOURCE EFFICIENCY IN THE PRODUCTION OF PAPER AND CARDBOARD (REVIEW)

Nowadays, Ukraine has chosen the European vector as the direction of its development. That is why industrial development must take into account the principles and norms of sustainable development and the circular economy. Ensuring resource efficiency is a necessary condition for the development of any enterprise. Due to economic and environmental restrictions, production of cardboard and paper products is being improved towards the use of waste paper, which leads to pollution of wastewater, and increased use of fresh water. An important problem in the use of waste paper is its polydispersity, which consists in the use of various cellulose fibers and fillers in the production of cardboard and paper products. Such polydispersity has a significant impact on the quality of the finished product and on wastewater pollution. The problem of effective treatment of industrial wastewater from paper production to obtain water for repeated use in the technological process, as well as the urgent problem of processing secondary waste from wastewater treatment remain unresolved. The issue of paper production development in the context of sustainable development should be developed taking into account technical and technological achievements in the field of ecology and chemical technology to ensure the efficient use of raw materials, in particular water and fibrous semi-finished products. The main problems associated with the use of secondary raw materials are described, taking into account environmental and economic aspects. Technological approaches, which allow to ensure the sustainable development of the industry, are described and analyzed. In general, the successful experience of European manufacturers in creating resource-efficient and clean technologies can be used as the basis for the further development of domestic enterprises.

Keywords: waste paper, wastewater, cardboard, sustainability, treatment.

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Technological features of paper and cardboard production from waste paper

The concept of sustainable development of society includes clear directions, namely social, economic and environmental, and aims to ensure the ability to meet the needs of current and future generations [1]. The main goal of sustainable development in the field of ecology is the development of effective water treatment technologies to ensure resource-saving production of consumer goods, which also include cardboard and paper products. The pulp and paper industry are a source of huge volumes of highly toxic wastewater due to the use of chemical compounds of various nature in their composition (Fig. 1).

Paper mills consume a huge amount of fresh water in production processes (~30–60 m^3 of water for the production of 1 ton of paper), and huge volumes of fibrous waste and polluted wastewater are generated [2]. Paper mill wastewater after paper production contains a large number of chemicals that are used at various stages of paper production [3]. The high content of organic and inorganic suspended solids in wastewater connected with the composition of the certain type paper and cardboard. Today, the paper industry makes a significant contribution to the global economy, providing other industries and the public with essential packaging and hygiene products [4]. Despite this, its impact on the environment is significant. The understanding of the need to apply innovative practices to ensure sustainable development is attracting increasing attention.

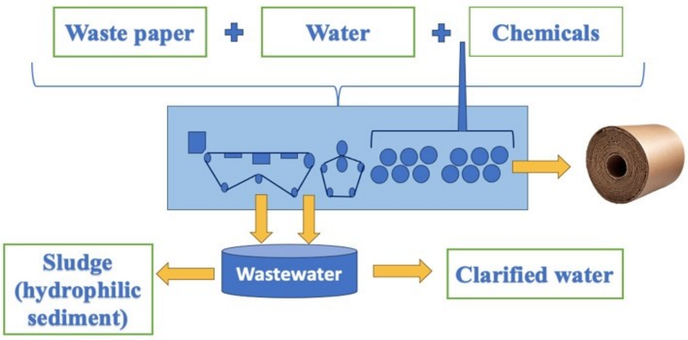

Fig. 1. Simplified scheme for obtaining paper and cardboard

In general, the production of paper and cardboard from secondary fibers is growing quite rapidly - approximately twice as fast as the production of paper from primary fibrous semi-finished products, which is due to both economic and environmental factors. Despite this, the increase in the volume of waste paper use is restrained by the gradual deterioration of the characteristics of secondary fibers, and by the constant increase in requirements for the quality of the final product and the effluents [5]. Recycling of paper provides the ability to reduce manufacturing expense. However, it should be noted that paper fibres cannot be recycled and reused constantly [6]. The optimal number of cycles of paper fiber reuse is up to seven times. Each round of recycling causes the breakdown of the fibres resulting in low paper strength properties [7]. The presence of short fibres and non-fibrous components in recovered paper causes additional wastewater pollution.

The main difference between waste paper fibers is their initial lower paper-making properties compared to primary fibers. As a result of the influence of a number of technological stages of preparation of fibrous mass (fibrillation, grinding) and production of paper and cardboard (pressing, drying, processing, etc.), as well as further processing processes (corrugation), fibers acquire new physical and mechanical properties, which are the cause of deterioration of the paper-making properties of secondary fibers. Secondary fibers are characterized by reduced strength of individual fibers, impaired ability to swell, hydration and fibrillation, increased tendency to shortening, as well as significant loss of ability to form inter-fiber chemical hydrogen bonds [8]. In the process of reprocessing waste paper, the following significant deterioration of its papermaking properties occurs [9].

Secondary fibers differ significantly from primary cellulose fibers in their physicochemical and morphological properties [10]. Secondary fibers can undergo several processing cycles, including grinding and drying, as a result of which their chemical and physical structure undergoes irreversible changes associated with the destruction of most pores and capillaries, redrying of the fiber surface, which prevents the diffusion of water into the fiber, and therefore its swelling. Redrying processes lead to a decrease in the specific surface area of the fiber, which is accompanied by a partial loss of the ability to form chemical bonds, which is the main reason for the deterioration of the physical and mechanical characteristics of the final product [11]. According to the composition, pulp from waste paper is a polydisperse pulp with a predominant content of short fiber. The presence of short fibers and their fragments causes not only an increase in the degree of grinding and deterioration of the dehydration of the paper mass on the grid of the paper machine, but also prevents the stabilization of the grinding process for the maximum recovery of the paper-making properties of secondary fibers [12].

In addition, short fibers are characterized by a weak ability to form intermolecular hydrogen bonds and reduce the mechanical adhesion of fibers during the formation of a paper sheet, which generally leads to a decrease in the strength of the finished product and to the contamination of the wastewater. To improve the quality of paper products from waste paper and to increase the degree of fiber retention on the screen, additive in a form of chemical reagents of various nature can be used to improve paper recycling [13]. Chemicals can be used to provide specific properties, water resistance, fiber retention, increase mechanical properties, improve ink retention, etc. [14, 15]. The volume of use of chemical reagents in the production of paper and cardboard has increased more than 2 times over the past 25 years. In the case of using waste paper, paper mills have a significant impact on water bodies and require the development and implementation of effective technologies for local and plant wastewater treatment.

Characteristics of paper mill wastewater

In the production of cardboard and paper products for various needs, a large volume of water is consumed to produce 1 ton of product (Fig. 2). Water consumption volumes may vary depending on production technology, technological equipment, and productivity.

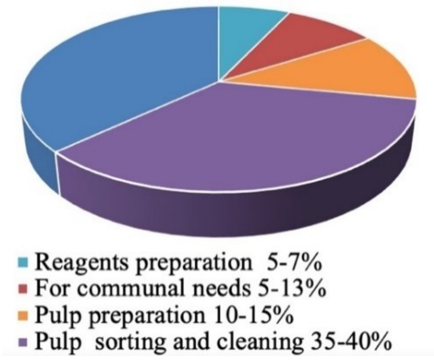

Fig. 2. Water use in paper production

In general, the volume and pollution of wastewater from paperboard and carton board production depends upon various factors such as type of raw materials, type and consumption of chemicals, type of final product and the efficiency of water recovery [15]. The pollutants discharged with effluents in paper industry are harmful to natural waters and negatively affect aquatic and land ecosystems causing liver damage, physiological changes etc. [16]. Common pollutants in paper mill wastewater include starch (either native starch or cationic starch), volatile fatty acids, various salts, fillers and pigments for coating, silicates, dyes and adhesives, aluminum sulfate, etc. These are measured as chemical oxygen demand. The composition and origin of typical pollutants in paper mill process water vary widely as shown in Table 1 [17].

Table 1

Characteristics of the wastewater from paper production based on wastepaper

Parameters	Units	Range of variation
pH	-	7.0-7.7
Chemical oxygen demand	mg/l	3770-9330
Biological oxygen demand	mg/l	816-2495
NH_4	mg/l	1.4-3.8
Total dissolved solids	mg/l	200-892
Total suspended solids	mg/l	603-8495

Contaminants cause problems throughout the papermaking process, such as reducing the effectiveness of additives, the optical and strength characteristics of the final product, the efficiency of sizing, and the deterioration of water transfer. Paper defects and paper web rupture can be caused by deposits and foam formation. The number of contaminating compounds varies from one production to another. Thus, despite its environmental friendliness, waste paper contains a wide range of pollutants that are formed as a result of paper formation, storage, and use. As a result of the dispersion of secondary fibers, pollutants diffuse into the process waters in the form of soluble and dispersed substances, which determine the composition and properties of the wastewater [19]. In addition to organic pollutants, wastewater also contains a number of inorganic pollutants. The presence of various salts is considered harmful to the course of the technological process, since their accumulation can be corrosive to machine parts and have a negative impact on the physical and mechanical performance of the final product. High concentrations of salts reduce the swelling potential of the fibers by increasing the osmotic pressure of the solution [20]. Wastewater from pulp and paper industries contains a large number of chemicals in soluble and suspended states, which are characterized by high toxicity, harm ecosystems, bioaccumulate and, ultimately, enter the food chain [21, 22].

The creation of comprehensive resource-efficient water purification technologies to ensure economical water use at paper industry enterprises in the production of cardboard and paper products is a relevant and important task of water purification technology and an important direction for the development of the domestic industry.

Wastewater treatment technologies in the production of paper and cardboard

Organizing water purification activities not only reduces water consumption and reduces the negative impact on the environment, but also allows you to return purified water to the technological process, which makes water use technologies cost-effective. The choice of water treatment technology, the level of water consumption reduction and the volume of recycled water reuse are different for each production, since wastewater pollution largely depends on the products produced [23]. A typical wastewater treatment process in the paper industry includes primary treatment (mechanical and physical treatment), secondary treatment (aerobic and anaerobic treatment), and tertiary treatment. Various processes have been investigated for the treatment of wastewater in the paper industry, including oxidation/reduction [24], membrane filtration [25], adsorption [26], biotechnology [27], etc. However, coagulation/flocculation processes are considered the most promising, as they are considered the simplest and cheapest [28]. Some significant advantages and noticeable disadvantages of the various technologies generally used for wastewater treatment are summarized in Table 2.

Table 2

Generalized characteristics of wastewater treatment technologies

Wastewater treatment method	Advantages	Disadvantages
Settlement	Easy to operate, as well as low cost of implementation and maintenance, is used as the first stage in water treatment technologies	Does not affect organic and inorganic pollutants in soluble form
Coagulation	Effective as a pre-treatment before flotation and membrane filtration; effective in removing suspended solids, dyes and some organic compounds; used in combination with flotation and membrane filtration	There is a need to use additional chemicals, which causes secondary water pollution, and sludge formation also occurs
Flotation	Effective in removing colloidal substances, suspended solids and hydrophobic substances	There is a need to use additional chemicals, sludge formation occurs
Biological treatment	Effectively removes substances that cause biological oxygen demand, as well as some soluble organic compounds	Requires strict control of water parameters before treatment, has no effect on inorganic components
Membrane filtration	Effective in removing pollutants of various origins, high quality of purified water	Characterized by low specific productivity, high operating cost, requires pretreatment of wastewater
Oxidation treatment	Promotes the breakdown of organic compounds, synthetic dyes	The formation of by-products takes place, the high cost of chemicals

In coagulation/flocculation processes, fine colloids present in wastewater are destabilized by the addition of coagulants. Coagulation is followed by flocculation, during which the destabilized particles are aggregated to form larger flocs that can be effectively removed by sedimentation [29]. The choice of wastewater treatment technology depends on the composition of the pollutants and very often involves the use of coagulation as the primary wastewater treatment [30]. Wastewater settling in combination with the use of coagulants is very often used for local water treatment in order to remove paper pulp components from the water with their subsequent return to the technological process [31]. Coagulation allows the removal of suspended solids, some toxic substances, and the reduction of color, chemical oxygen demand, and biological oxygen demand [32]. The most common coagulants are aluminum salts, iron salts, and polyelectrolytes [33]. The sludge produced by chemical coagulation with polyvalent metals is often harmful, contains hydroxides and often has a high pH. Sludge treatment, transportation and disposal are quite expensive. Iron salts such as ferric chloride and ferric sulfate, despite having a similar valence to aluminum and lower cost, impart additional color to the wastewater, resulting in the formation of colored organic compounds [34-36].

Currently, aluminum-based polymer coagulants with the formula $(Al_n(OH)_mCl_{(3n-m)})_x$ are widely used, in particular polyaluminum chlorides (n = 2 and m = 3), aluminum chlorohydrate (n = 2 and m = 5), the hydrolysis of which occurs with the formation of various mono- and polymeric forms, and a particularly important cation is $Al_{13}O_4(OH)_{24}^{7+}$ [37]. Basicity is an important property of polyaluminum coagulants. This is the ratio of hydroxide to aluminum ions in the hydrated complex, so polyaluminum coagulants generally consume significantly less alkalinity than aluminum sulfate, reducing the pH of the treated water less and minimizing the need for pH correction. Thus, polyaluminum coagulants are effective over a wider pH range compared to aluminum sulfate. In addition, such coagulants are also inexpensive, having a fast-settling rate and low turbidity, and are suitable for the treatment of wastewater containing starch [38]. Biopolymers of natural origin can also act as coagulants, in particular chitosan, which can remove colloids and dissolved organic substances. As a result of coagulation, a high-density precipitate is obtained [39]. Polyacrylamide is also widely used as a flocculant, which, due to its high molecular weight, forms large agglomerates. There are different types of polyacrylamide coagulants of cationic, anionic and nonionic types, which are able to adsorb pollutant particles with different charges [40].

As a result of local wastewater treatment at paper mills, huge volumes of sludge (waste of fibrous and inorganic nature) are formed, which, depending on the type of production, can consist of 50-80% mineral components. Today, incineration and landfilling are the two preferred methods of its disposal. However, both methods are economically and environmentally unattractive. The high moisture content (more than 50%) is a major problem of the waste that needs to be addressed before landfilling or incineration [41]. To avoid the dehydration and drying stages, the conversion of polysaccharide components of osprey into sugars, bioethanol, and biogas was developed [42, 43]. It is worth noting that the presence of a large amount of mineral component in sludge has a negative effect on enzymes, namely, it inhibits their activity. Removal of mineral components requires additional reagents and equipment. An important fact is that only a small portion of the sludge can be used again to make paper and cardboard.

Biological treatment is used in plant-wide treatment schemes. It is used to remove organic suspended solids, as well as colloidal and dissolved organic compounds and this contributes to the reduction of chemical oxygen demand, biological oxygen demand and color of water [44]. At the same time, biological methods are cost-effective and regarded as environmentally friendly compared to physico-chemical purification, biological processes are less effective in removing color compounds. In addition, pollutants and different toxic chemicals, including unsaturated fatty acids, chlorinated hydrocarbons and alcohols, negatively affect the effectiveness of biological treatment methods. To achieve the required water quality indicators after biological treatment, physicochemical methods are always used, which consist of settling and filtering using bulk filters or membrane technologies. The modern approach to organizing biological treatment is to obtain not only purified water, but also bioenergy materials to meet energy needs [45].

Waste minimization model to ensure sustainable paper and cardboard production

The development of the domestic and global pulp and paper industry should take place in compliance with the principle of greening production. In this regard, several main directions have been identified: 1) reduction of fresh water consumption in technological processes; 2) increasing the share of secondary fibers, as well as fibrous-inorganic sludge from wastewater treatment; 3) developing alternative sources of fibrous materials for the production of paper and cardboard; 4) reducing greenhouse gas emissions; 5) ensuring clean production.

Nowadays, the needs to reduce freshwater consumption in manufacture of paper and board and to meet existing discharged standards have forced mills of industry to treat wastewater using different techniques of treatment. The conventional treatment processes that can be used for effluent treatment include physicochemical and biological methods [46]. Conventional methods deal very often with secondary pollution of wastewater and high energy supply [47]. Physicochemical methods are sedimentation, filtration, precipitation, coagulation and flocculation, oxidation, adsorption, sludge treatment [48]. Coagulation and flocculation have been the most widely spread techniques for the removal of organic suspended and dissolved solids from wastewater using chemical coagulants such as aluminum sulfate, ferric chloride, polyelectrolytes. Additional chemicals for sludge treatment and wastewater treatment are used in the form of coagulants, flocculants and sorbents to increase mass retention on the grid, intensify wastewater clarification processes and treat the resulting sludge [49].

The problem of wastewater pollution can be solved through an integrated approach in the technologies of industrial wastewater treatment, as well as taking into account all the features of cardboard and paper production, including the selection of pulp components and its preparation, the formation of paper sheet, and the processing of pulp. More attention should be paid to the issue of reducing the amount of illiquid waste paper fiber by replacing it with primary cellulose fiber of domestic production from available cheap raw materials using delignification by-products as sorbents in water treatment technologies. It is also important to develop effective sorption materials for the absorption of synthetic dyes from wastewater using "green chemistry" approaches [50]. It is relevant and important for solving a number of environmental problems, in particular, the use of illiquid multi-tonnage non-fibrous plant waste from the agro-industrial complex can be an alternative to traditional industrial sorbents for the effective removal of synthetic dyes from wastewater.

The use of waste paper and paper sludge in the production of paper and cardboard is of great practical importance, since under these conditions the volume of solid waste from wastewater treatment is reduced. However, the full use of sludge in the composition of paper and cardboard is limited by high requirements for the quality of the final product. As a result of the cyclic multiple use of waste paper, its paper-making properties deteriorate, the content of short-fiber and mineral components increases. The presence of inorganic components has a significant impact on the formation of inter-fiber hydrogen bonds in the paper sheet, which ensure the strength of the paper sheet. In conditions of increasing sludge consumption, it is important to ensure both effective purification of the wastewaters and the required quality of the final product. The complex problem that has arisen can be solved by using starches as additives. However, the use of native and some modified starches is ineffective, since wastewater pollution occurs due to the leaching of starches, due to their low adsorption on cellulose fiber [51]. High leaching of chemical reagents leads to a deterioration in the quality of circulating water, a decrease in the concentration of dissolved oxygen, the development of slime-forming microorganisms, biofouling of technological equipment, its corrosion, the appearance of unpleasant odors, and a deterioration in the quality of finished products [52]. It should be noted that cationic starches are more effective, but the vast majority of them are imported from abroad, their cost is quite high, and this affects the cost of finished products.

In the case of using primary fiber as the starting material, wastewater is less polluted compared to wastewater from technological processes based on the use of secondary raw materials - waste paper. However, in the case of using wood pulp obtained by traditional methods of cooking with chemical reagents used in the production of cellulose products, in particular soda, sulfates, chlorine derivatives. Taking into account all these aspects, it is worth noting that the use of cellulose obtained by organosolv cooking methods is attractive from the point of view of creating rational water use systems at paper industry enterprises, which eliminates the need to use sulfur compounds for cooking and chlorine compounds for bleaching [53]. In this case, the wastewater of paper enterprises will contain mainly cellulose fiber, which, under the conditions of organizing effective local treatment, can be returned to the production process. Under the conditions of local treatment of such wastewater, it is possible to achieve deep clarification, which will allow using clarified water for technological needs.

Addressing the issue of effective wastewater treatment, waste paper recycling, and paper sludge application in a complex will have a positive impact on reducing greenhouse gas emissions. As for ensuring clean production, this need is due to the fact that the pulp and paper industry is one of the largest sources of pollution of water bodies in the world, as well as one of the largest consumers of fresh water and energy (about 6% of global energy is used) [54]. Key principles of clean production include the optimization of production processes, waste reduction strategies, use of energy-efficient equipment, and continuous improvement efforts.

Conclusions

The most promising areas that ensure the implementation of efficient water use, saving fresh water, and reducing the volume of solid waste generation at mills engaged in wastepaper processing are the use of auxiliary chemicals to reduce the turbidity of under-screen waters or partial replacement of secondary fiber with primary fiber. It is important to create an effective water treatment technology for the reuse of under-screen waters in technological processes and to ensure the reuse of under-screen waters from local cleaning in paper production using strengthening additives, flocculants and coagulants, as well as effective technology for its dehydration and utilization. Another unresolved task remains to ensure effective cleaning of under-screen waters by reducing fine fiber sediments in technological processes for the production of paper and cardboard by partially or completely replacing secondary fiber with primary cellulose using available raw materials, for example, straw and stems of non-woody plant raw materials.

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