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Review

Paper-Mill Wastes for Bioethanol Production in Relation to Circular Economy Concepts: A Review

Dafna Or-Chen [1], Yoram Gerchman [2,3], Hadas Mamane [1] and Roi Peretz [1,*]

[1] School of Mechanical Engineering, Faculty of Engineering, Tel Aviv University, Tel Aviv 6997801, Israel; dafnaedelman@gmail.com (D.O.-C.); hadasmg@tauex.tau.ac.il (H.M.)
[2] Oranim College of Education, Tivon 3600600, Israel; gerchman@research.haifa.ac.il
[3] The Institute of Evolution, University of Haifa, Haifa 3103301, Israel
* Correspondence: peretzroi10@gmail.com; Tel.: +972-548-034-652

Abstract: This review explores circular economy principles in regard to ethanol production from paper-mill sludge. Environmental sustainability and renewability over fossil fuels make second generation ethanol an attractive energy source in a rapidly growing population and consumption world. Paper sludge (PS), a by-product of the pulp and paper (P&P) industry, can no longer be recycled for paper production and is mainly disposed of in landfills. Therefore, it poses a major environmental challenge. However, it has shown potential as a valuable raw material for ethanol production, along with other pulp and paper products, due to its abundant availability and high cellulosic content. This waste-to-energy (WtE) technology for ethanol production is proposed as an alternative, aligning with circular economy concepts to maximize resource efficiency and minimize waste. This review underlines the circular economy aspects of bioethanol production within paper mill sludge management systems. Circular economy principles applied to ethanol production from PS offer a promising avenue for sustainable biofuel development that not only addresses waste management challenges but also enhances the overall environmental performance of biofuel production. Furthermore, economic benefits are described, highlighting the potential for job creation and community development.

Keywords: paper-mill wastes; bioethanol; waste management; waste-to-energy; circular economy

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1. Introduction

The increase in world population, urbanization, industrialization, and remote commerce has resulted in a higher demand for energy, water, land, as well as waste and pollution production. Currently, most municipal solid wastes are either landfilled or disposed of in open dumps [1,2], an environmentally harmful practice that is being criticized in many countries. Figure 1 shows the total wastes being disposed of by landfilling and open dumping out of the total waste generation for different geographical regions around the world. Reaching negative carbon emissions in a decade will require the adoption of strategies such as the reduction of fossil fuels like oil and natural gas, implementation of carbon capture and storage (CCS), implementation of bioenergy with carbon capture and storage (BECCS), and an increase in the use of renewables and biofuels [3].

Paper and cardboard wastes originate from wood materials and are composed of 40–80% cellulose, 5–15% hemicellulose, and minor traces of polyphenolic lignin [4]. The high cellulose content of these wastes suggests they can be valorized for many applications. Different valorization options have been suggested, including their use as feedstock for nanocellulose, building materials supplementation, or bio-gas production [5]. Nevertheless, none of these solutions were viable, resulting in most of the world's paper and cardboard wastes being landfilled or discarded in open dumps, causing significant environmental issues such as groundwater contamination, greenhouse gas emissions, and accelerated

landfill filling [6]. The P&P industry is one of the major consumers of woody biomass, and consequently, major producer of cellulose-rich wastes. Thus, wastes originated from the industry, such as kraft pulp and sludge [7], are suitable for bioethanol production despite their low quality.

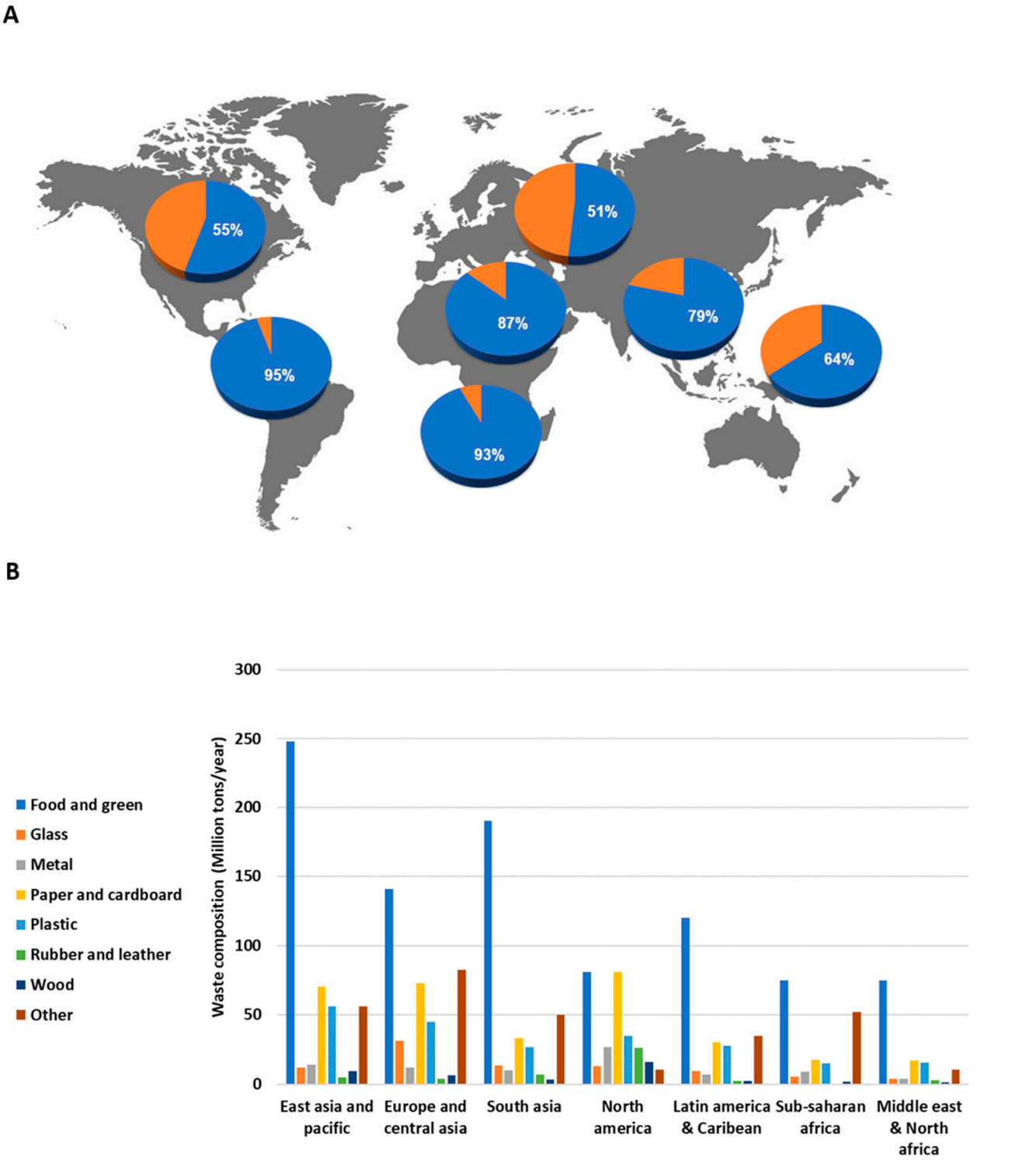


Figure 1. (**A**) Worldwide landfilling and open-dump disposal rates. The landfilled fraction of the wastes for each geographical region is represented by the blue color (**B**) Global waste generation, based on data from [2].

Recycled paper sludge (RPS), a paper production by-product, is an excellent lignocellulosic biomass source for bioethanol production due to its high cellulose content and negative cost [5]. Converting RPS to bioethanol aligns with circular economy (CE) concepts and is key in achieving Agenda 2020 for America's forest, wood, and paper industries [8,9]. Paper is a well-explored material, including its production process, waste product, and properties. However, there has been a decline in the number of publications specifically addressing paper and paper-waste materials in 2022. The CE topic, however, has increased dramatically in publications and research since the mid-century, as observed in the Web of Science and Scopus databases (Figure 2). Models and ideas for adapting circularity concepts in industries are in line with sustainability.

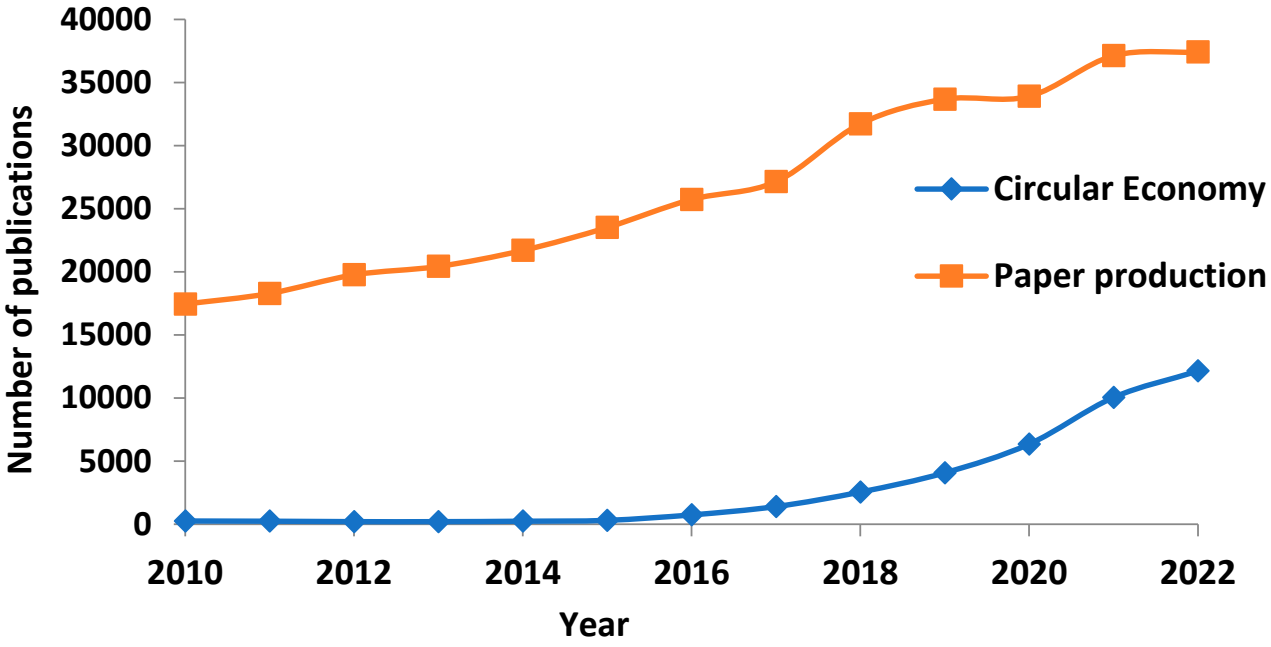


Figure 2. Number of publications about paper products and circular economy, averaged across Web of Science and Scopus databases from 2010 to 2022. Paper production was defined by the keywords "Paper sludge", "Papermaking", "Paper products", and "Waste-paper".

The valorization of RPS cellulose requires a pre-treatment stage to release the cellulose fragments. This stage is commonly viewed as the limiting factor in the process, both in terms of cost efficiency and sustainability. Ozonation has been shown to be an effective and eco-friendly method for pre-treating paper waste in the production of bioethanol [10,11], and it has been applied in various stages of paper production and advanced treatment of wastewater [12]. Since RPS cannot be recycled, it can be used as a source for waste-to-energy (WtE) as the preferred option. Moreover, WtE does not have to compete with recycling but rather with landfill, which is lower in the waste hierarchy [13].

As current economy is mostly based on a linear and open-ended system, it compromises sustainability and the ability to meet future needs. CE addresses this sustainability issue, proposing a cyclical material and energy flow model. Biorefining for ethanol production is a crucial step towards CE, as it allows closing the loops for biomass, water, and carbon and maximizing valorization. The present paper reviews CE aspects in the production of bioethanol from paper sludge.

Biofuels have the potential to play a significant role as a supplier of energy [14]. Developing gasoline substitutions for the transportation sector is of high importance, with ethanol starting as a globally adopted alternative, as evidenced by the increase in annual world production from 13.0 billion gallons in 2007 to about 25.6 billion gallons in 2015 and expected to reach 36.9 billion gallons by 2023 [15,16]. Bioethanol is currently produced

mainly from especially grown crops, e.g., sugarcane and corn, but it could be generated from cellulose-rich biomass (i.e., 2nd generation bioethanol), like RPS, as cellulose is a glucose polymer. Organic lignocellulosic materials, sourced without using agricultural land or impacting human food resources, are recognized as highly economical for the energy industry. Predictions indicate a forecast of a dramatic acceleration in 2nd generation biofuel production after 2030 and eventually meeting 26% of total transportation fuel demand by 2050 [17].

2. Paper and Cardboard Manufacturing Process

2.1. Paper and Cardboard Feedstock Materials

Despite a decrease in printing and tissue paper production, the global paper and paperboard industry has been steadily increasing [18]. Paper and cardboard consumption has risen over the past 10 years by 6.5% to over 423 million metric tons annually worldwide. Correlating with this, annual paper and paperboard production is expected to grow to between 700 million metric tons (low estimate) and 900 million metric tons (high estimate) in 2050 [19]. The most significant increase in manufacturing volumes is seen in Latin America and Asia, specifically India and China (Figure 3). On the other hand, the leading paper-importing countries are from Europe and North America, primarily the United States, Germany, and France, which import 22.5% of global paper products [20,21].

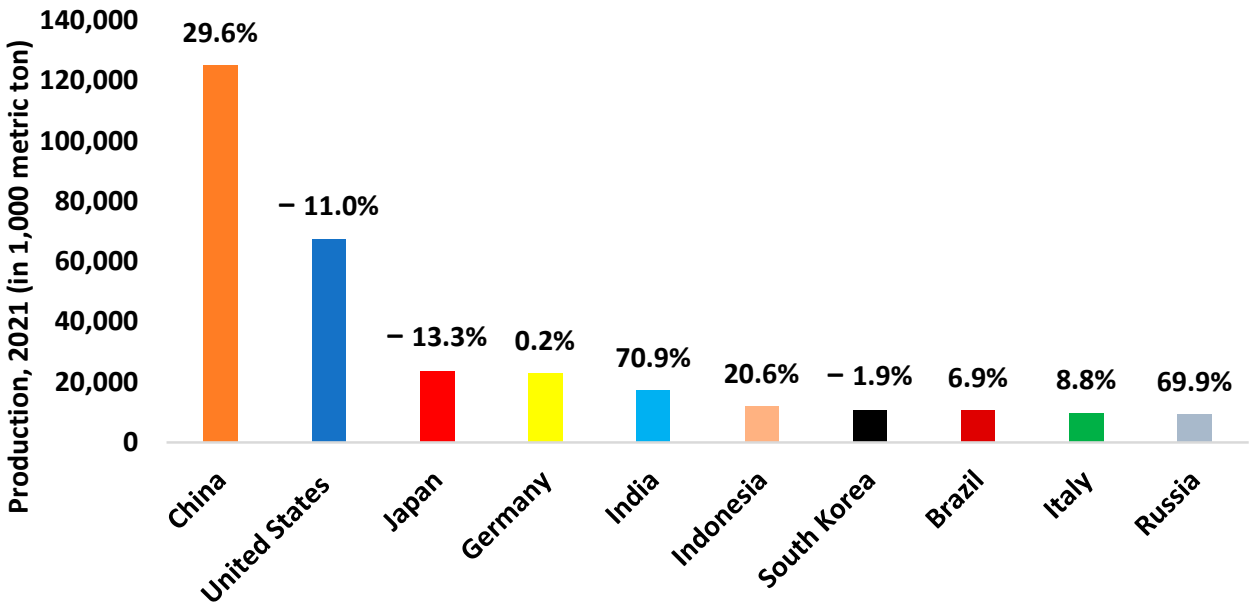


Figure 3. Worldwide major paper and cardboard producers, 2021. The upper labels refer to changes in production compared to 2010.

The practice of papermaking from wood sources dates back the 19th century, utilizing process principles that remain relevant today. Essentially, there are two main steps in the production of paper. The first step involves converting fibrous raw material into pulp, and the second step transforms this pulp into paper.

The raw material used for paper production is mainly wood, which can also be recycled into secondary fibers and non-wood materials (e.g., cotton, hemp, and flax). P&P mills receive wood logs that are then chipped for pulping. The wood material can be divided into hardwood (short fiber wood), which comes from angiosperm or flowering plants (such as oak, maple, or walnut), and softwood (long fiber wood), which comes from gymnosperm trees, usually evergreen conifers (like pine or spruce). Most hardwoods have a higher density and a higher price than softwoods. Table 1 shows the chemical composition of softwoods and hardwoods.

Table 1. Composition of softwoods and hardwoods, adapted from [22].

Compound	Chemical Composition (%)	
	Softwoods	Hardwoods
Cellulose	40–44	45–50
Hemicellulose	25–29	25–35
Lignin	26–31	18–24

Fibers are longer in the softwood matrix than in hardwood [23,24]. While both wood fibers can be used for papermaking, different paper properties can be achieved according to the feedstock raw material. Papers made from hardwood exhibit higher ink absorption abilities and overprinting precision. This is attributed to a higher content of fine fibers [25]. In addition, while shorter fibers exhibit less flexibility and slenderness ratio, short and thick fibers show even poorer values [26]. Pulps with longer fibers, high-coarsened, and low-fine content have shown to provide higher water absorbance ability. In addition, long fibers with thin cell walls can increase paper strength without affecting softness [27]. Nevertheless, in several developing countries, about 60% of the cellulose used for papermaking originates from non-wood materials, such as bagasse, rice straw, jute, grass, and bamboo. In China and India, for example, 70% of the raw materials in the pulp industry originated from non-wood materials. These two countries account for 80% of the total non-wood pulp production [28,29].

2.2. Pulping Process

The pulping process refines raw material into fibers to form paper or paperboard. During pulping, cellulose fibers are broken apart by mechanical and/or chemical digestion to optimize paper strength. This includes digestion and shearing at elevated temperature and pressure, resulting in fibers swelling and straightening out and creating fines. This process can cause the fiber's internal area to collapse, leading to an increased bonding area, although the bulk (density) of the paper is decreased [30]. Pulping can be done by mechanical, chemical, or semi-chemical pulping methods. The selected pulping method is based on the properties required in the final paper and considers the fiber's morphology and characteristics.

Mechanical pulping grinds and shreds the wood chips and can convert up to 95% of wood's dry weight [31], yet requires a large amount of energy. Fibers produced by mechanical pulping are lower in strength than chemically pulped and are mainly used for newspaper and non-permanent paper products [32]. Chemical pulping is mainly done by the kraft pulping method [33]. In this method, alkaline solutions (NaOH and Na_2S) at 155–175 °C are used to produce writing paper, paper bags, and specialties. During this process, lignin is degraded into smaller alkali-soluble fragments, mainly through the cleavage of α- and β-aryl ether bonds, which leaves the cellulose fibers intact. The delignification rate decreases at around 90% lignin removal, probably due to the remaining alkali-stable bonds between lignin and polysaccharides/hemicelluloses and within lignin. Since the selectivity of delignification is reduced at that stage, the process is stopped at a maximum of 95% delignification, and the remaining lignin is removed by bleaching agents [34]. Other chemical pulping methods use sulfuric acid (sulfite pulping). These processes allow easier bleaching due to the oxidative nature of the acids. However, the resulting pulp is less strong than kraft pulping [32]. Semi-chemical pulping combines mechanical processes with chemicals. An example of semi-chemical pulping is utilizing natural substances, such as Na_2CO_3, followed by the mechanical separation of the fibers. As the generated pulp in such a process is rather stiff, it is mainly used for corrugated carton [32,35]. Since printing and writing paper have higher demands while newspapers have a negative growth rate, chemical pulp has become dominant, while mechanical pulp has been reduced in volumes [36]. Additionally, the environmental impact of the kraft

process is smaller, as the chemicals in use are simple, and the energy recovery system is efficient [37].

Delignification degree is determined by a redox reaction. The result is presented by the kappa number, which is an important mill control parameter. The higher the kappa number, the higher the lignin content in the pulp. If the kappa number is too low, the pulp yield and physical properties will decrease considerably [38]. Recent studies show that cellulose pulp with a kappa number of 64 is considered to be optimal, based on pulp properties and expected costs. Both the tear index and the produced paper area of paper made from that pulp exhibited the highest score of 6.13 mN $\times$ m^2/g and 5596 m^2 from 1 metric ton of wood. The total paper production yield was 45.7%, only slightly less than for pulp, with a high kappa number of 89.7, with 47.2% [39].

2.3. Bleaching

Bleaching processes remove remaining lignin and brighten the pulp using a few chemical operations (typically three to six), of which one is aimed at hemicellulose removal by acids or alkali treatment [40]. Typically, an alternating series of bleaching and extraction steps is employed. In the bleaching stage, the pulp is treated with oxidizing chemicals, and in the extraction stage, it is neutralized by other chemicals, such as sodium peroxide. The chemicals can be grouped into two categories: chlorinated (such as elemental chlorine, hypochlorite, and chlorine dioxide) and non-chlorinated (such as oxygen, peroxide, and ozone) [41]. A combination of the various types, especially when chlorinated chemicals are first in the process, is very common. However, the trend of totally chorine-free (TCF) pulp processes has been gaining ground [42]. The bleaching chemicals are thoroughly mixed with the pulp by rotary high-shear or static mixers to minimize chemical waste and contamination and increase pulp quality. Each bleaching stage needs a specific temperature, pressure, and retention time, which are all maintained in towers for each process [43].

2.4. Papermaking

After bleaching, the fibers are added to water to generate a slurry consisting of approximately 99.5% water and approximately 0.5% pulp fiber [32]. The fibrous mixture pours from a headbox onto a traveling wire mesh or a rotating cylinder and later goes through presses and heated cylinders, which remove additional water and continue the formation process. About 90% of the cost of removing water from the sheet is for the energy required during the pressing and drying operations [44]. The water removed from the fibers, known as white water, is commonly reused as washing water in this same process [44,45].

Before entering the calendaring process, which is part of the finishing, the paper web can continue into a second drying operation. The target moisture content is 4–6%, depending on the mill, to prevent over-drying and paper embrittlement. Depending on the final product, the papers can undergo additional processes such as sizing and coating with clay or other pigments and/or adhesives in order to cover the surface peaks (knobs), fill the voids, and unify the thickness, to improve printing quality, color, smoothness, opacity, or other surface characteristics. Most coated paper is made from mechanical pulp, at least in one of the layers. Coating is mostly done by the blade-coating method, which not only fills the paper voids but also applies pressure on the peaks of the base paper [46]. In addition, fillers are added to the slurry before the formation of the paper web. These are pigment powders produced mainly from water-insoluble natural minerals that combine elements such as carbon and calcium with particle sizes of roughly 0.1–10 μm [47]. The most common fillers used in papermaking are ground calcium carbonate (GCC), kaolin, precipitated calcium carbonate (PCC), talc, and TiO_2. In printing and writing paper, GCC and kaolin are both used by almost 40% of mills. Talc and TiO_2 are consumed in quite small quantities and only for special applications [48]. The main motivation for using fillers is their low cost compared to fibers and their ability to improve optical and surface properties

in the final product. However, the use of fillers brings challenges in papermaking, such as poor binding resulting in lower paper strength, which limits its use [49].

2.5. Paper Grades and Properties

Paper and paperboard are assessed for properties such as basis weight (in mass/area units) and caliper (thickness in length units). For printing paper and paperboards, the grade represents the printing ability, converting quality, and the color of the paper. Paper strength, indicating its resistance to rupture when stresses are applied, is a very important parameter that is affected by the fiber strength, length, and inter-bonding. The refining process and the structure of the sheets also impact the paper strength [50]. Moreover, papers of higher grade are often made of several layers and a coated and/or calendared surface. Water absorption of the coated paper decreases by at least 50% vs. uncoated, which significantly affects the dimensional stability of the paper during web offset printing [46].

In the paperboard category, there is a hierarchy of grades based on the pulping, bleaching process, coating, number of plies, and the content of the base layer. Solid bleached sulfate (SBS) is the highest grade, which is a clay-coated multi-layered structure of virgin bleached fibers that presents high printing quality and good looks as it is white throughout. SBS is extensively used in food packaging, and therefore its use is governed by strict requirements for hygiene, purity, and odor. The coated unbleached kraft (CUK) is a lower grade as it contains unbleached kraft fibers that remain brown. The fibers used for this paperboard are large and long, hence the paper strength is very high. Coated recycled paperboard is of a lower grade as its body is made of recovered fibers, and it has a top white ply and a clay coating to improve printability [18].

The tissue paper category includes toilet paper, paper towel, napkins, etc. Toilet paper is generally made from softwood and hardwood virgin fibers. Other types, like paper towels, may be produced from recycled paper. The manufacturing process is like kraft pulping, with an additional step of creping, especially for sanitary papers. In this process, the paper is dried on a jumbo cylinder and then scraped off with a metal blade, slightly crimping it. This softens and weakens the paper to allow it to disintegrate in water [31].

2.6. Paper Recycling

Paper is one of the most recycled materials [12], and 58% of paper is recycled globally [49]. As a result, recycled paper is a growing share of the paper industry. For example, more than two-thirds of Indian mills use waste paper as the primary fiber source, contributing to 47% of the country's total production of paper, paperboard, and newsprint. The average recycled fiber content ranges between 93% and 95% for case materials and newsprint to just over 12% for other graphic paper [32,51,52]. Practically, paper can only be recycled five to seven times since part of the fibers gets lost during recovery or gets shortened. In addition, paper results in 30–75% loss of its material value after one use [53]. Recycled fibers' properties and quality change according to their source (Table 2).

The processes of pulp derived from wastepaper can be generally divided into four parts: de-fiberization, dirt removal, de-inking, and bleaching. First, the secondary fibers are inserted into a large mixed tank in which the paper matrix is dissolved with the assistance of hot water or chemicals. Then, dirt, residuals, and contaminations are removed by raggers-wires that the dirt can accumulate on and junkers-collectors of heavy debris that are separated in the pulp centrifuge. In the de-inking stage, floatation practice is commonly used for separating the ink from the substrate with bubbles floating in a liquor. Alkali substance (such as NaOH) is added to the pulp slurry to detach ink from the fibers. The hydrophobic ink particles attach to the hydrophobic bubble's surface, and the bubbles rise and are removed from the liquid tank. Several studies have demonstrated ozone addition to the de-inking process for reducing chemical oxygen demand (COD) levels, in addition to ink floatation [54–56]. After de-inking, the pulp goes into the bleaching process (as described in Section 2.3) to remove excess lignin and brighten the fibers [57].

Table 2. Paper grades for recycling [58].

Grade	Quality	Examples
1	Low	Corrugates board, unsold magazines, mixed magazine and newspaper, mixed-paper, and paperboard
2	Medium	Newspaper, printed white shaving, sorted office paper, PE-coated paperboard, colored wood-free paper
3	High	Wood-free binders, white wood-free paper, SBS paperboard, coated mechanical pulp paper
4	Kraft	New shavings of corrugated board, used kraft paper
5	Special	Liquid packaging paperboard, wet-strength wood free paper, and labels

2.7. Manufacturing Process in Hadera Paper Mill, Israel: A Case Study

Hadera Paper mill ("Infinia" group) is the largest paper and cardboard production and recycling factory in Israel. There has been a substantial increase in paper and cardboard recycling over previous years due to the operation of a new packaging facility that recycles cardboard and the improvement in cardboard collection, including from landfills. Paper waste is typically recycled multiple times (2.4 times in average), but through the recycling process, the fibers are shortened by mechanical erosion, resulting in large amounts of short fibers (up to 40% of input mass), termed recycled paper sludge (RPS). These short fibers are rich in cellulose but are currently disposed of in landfills, causing landfill filling, greenhouse gas emissions, and groundwater contamination. Table 3 shows the RPS material composition. The very high cellulose content of the RPS, and since RPS cannot be further used for paper recycling, makes it a very good feedstock for 2nd generation ethanol production and other cellulose-based products like cellulose nanocrystals (CNC's) [5,59], and eventually solve the costs for disposal of the paper waste sludge waste.

Table 3. RPS characteristics (dry basis), adapted from [60].

Moisture (%)	40–45
Insoluble lignin (%)	8.22 ± 0.22
Soluble lignin (%)	10.71 ± 2.21
Crystalline cellulose (%)	75.30 ± 20.20
Ash (%)	16.64 ± 2.21

The cardboard recycling facility in Hadera Paper and its wastes are illustrated in Figure 4. In the process, the raw material is made into a slurry in the pulper by mixing with water, where rejects are separated. This waste stream consists of low fiber content and a high content of plastics. Currently, this stream is landfilled but is evaluated as a future incrementation additive in power stations.

The fiber slurry flows through a high and low consistency cleaner (HCC and LCC, respectively) and to a fiber sorter where rejects are transferred to the reject flow. The fractionator separates the fibers to long fibers (4.7% conc., >2.6 mm) and short fibers (2.2% conc., <2.6 mm). The long fiber undergoes fine cleaning, and the residues are collected on an extra-fine screen where the filtrate is the RPS. This RPS can also undergo mechanical de-watering processes such as Belt Filter Press or Screw compressors.

Hadera Paper mill generates 31,000 tons of cellulose-rich RPS per year. Furthermore, given the recent advances in packaging material collection ("Container law") and the large quantity of paper and cardboard product in this waste, it is likely that more cardboard will be recycled in the future, and accordingly, more sludge will be generated. To date, this waste is used for dairy barns. Several publications have examined it as feedstock

for bioethanol production [61–63]. A recent publication showed the conversion of RPS to ethanol using the ozonation process as a pre-treatment stage, resulting in 94.42 ± 0.013 g ethanol/kg RPS [5], but with a higher yield and shorter hydrolysis time.

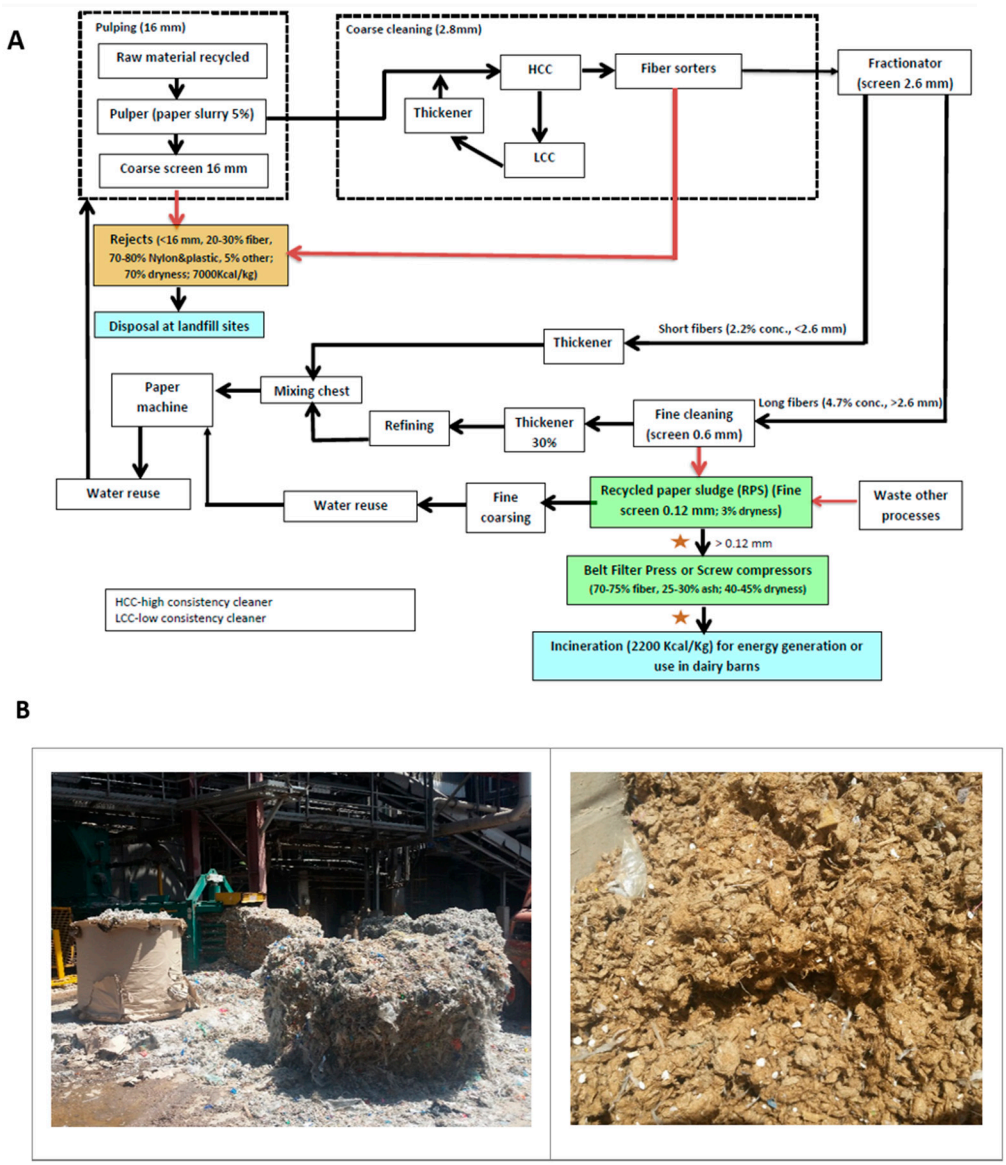


Figure 4. (**A**) The cardboard recycling facility in Hadera Paper. The star denotes the place in the process where RPS will be examined for bioethanol production as a replacement for existing solutions (incineration or dairy farms). (**B**) Recycled Paper Sludge (RPS).

3. Paper Mill Wastes

3.1. Global Solid Waste and Paper Waste

Countries with higher income and higher gross national income (GNI) tend to produce more waste. With urbanization, solid waste increases dramatically, with paper being one of the growing segments [64,65]. Municipal solid waste management (MSWM), as part of the wider circular economy concept, is a critical element for countries aiming to move to sustainable metropolises, and it includes segregation, storage, collection, processing, and disposal of solid waste. MSW, and the paper fraction of it, vary widely around the world (see Table 4).

Table 4. Waste and paper recycling.

Country	Paper Production (MTons)	Paper Consumption (Million Metric Tons)	MSW (kg Capita^{-1} Day^{-1})	% Paper within MSW (% wt.)	Paper Recycling Rate (%)	References
Argentina	1.3	1.9	1.2	N/A	N/A	[66]
Australia	3.4	3.5	1.8	6.7	53	[3,66]
Belgium	2.1	2.8	1.3	N/A	60	[66]
Brazil	14	9	1.1	13.1	63.4	[67]
China	125	109	1	8	35	[66,68]
Egypt	0.7	1.7	1.4	10	N/A	[66,69]
France	8	8.7	1.5	16.2	54	[66,70]
Germany	22.6	20.5	1.7	8.1	83	[66,71]
Greece	0.4	1	1.4	20	37	[66,72]
India	17	17	0.4	6	29	[66,73]
Iran	0.8	1.8	0.2	7.8 *	N/A	[66,74]
Israel	0.4	0.9	1.7	24	39	[75]
Italy	8.9	10.5	1.4	19	46	[66,76]
Japan	26.1	26	0.9	N/A	72	[66]
Korea	11.6	9.5	1	35	85	[66]
Malaysia	1.8	3.1	0.9	17.8	N/A	[64,66]
Mexico	5.7	8.9	1	5.89 *	7	[66,77]
Pakistan	0.9	1.4	0.7	2.4	N/A	[64,66,78]
Portugal	2.2	1.2	1.2	27	50	[66,79]
Poland	4.6	6.4	0.9	19.1 *	34	[66,78]
Russia	8.5	6.9	0.9	N/A	N/A	[66]
Saudi Arabia	1.2	2.1	1.3	28.5	N/A	[66,80]
Singapore	0.1	0.5	0.9	21.2	40.3	[64,66,81,82]
Spain	6.2	6.7	1.3	27	59	[66,83]
South Africa	2.2	2.3	2	18.2	59	[66,84]
Turkey	3	4.9	1.1	15	38	[66,85]
United Arab Emirates	0.2	0.9	1.7	22	N/A	[66,86]
UK	3.7	8.9	1.3	10.5	56	[66,87]
USA	73	70	2	26	50	[88]

* Data from the capital/biggest city; N/A not available.

3.2. Waste Cycle in Pulping and Bleaching Processes

Paper production also results in waste stream generation, mainly during the pulping and bleaching stages. Kraft pulping results in a stream of weak black liquor containing ~15% total solids, including spent chemicals and solubilized biomass. This weak black liquor is concentrated in evaporators, resulting in 70–80% total solids [36,41]. The produced heavy black liquor is then recovered and burned by spraying it into recovery boilers. Salt smelt, consisting mainly of Na_2CO_3 and Na_2S, is generated and leached in water, generating green liquor. The green liquor is causticized to form white liquor, which is recovered and reused in the pulping process, as well as in washing water [89]. The thickened pulp moves on to the bleaching process [41]. The bleaching stage is the major source of effluent in a pulp mill (up to 85%), and the chlorinated effluents are more complicated to treat for reutilization within the mill [32]. Most compounds identified in bleaching effluents are derived from lignin or other wood components [12,56]. There is also a large amount of colored pollutant compounds (200 to 300 kg ton^{-1} of pulp), mainly chloro-lignin, which are resistant to conventional biological degradation. One of the most effective treatments for bleaching effluents is a combination of ozone with fixed bed biofilm reactors, which provides maximum elimination of COD substances with a minimal dosage of ozone. This technology transfers the oxidative residue into a biological excess sludge. It was found that ozone addition upstream from bio-filtration not only enhances the biodegradability of

dissolved organics but also introduces a large amount of oxygen to the water, which is a favorable environment for biological growth on the filter media [56].

3.3. Waste-Water Treatment and Paper Sludge

The paper industry stands out as one of the largest consumers of industrial process water and energy (per product ton). In the United States, it leads in industrial water consumption and ranks third in energy consumption. Additionally, it holds the fourth position among industrial sectors in emissions of toxics release chemicals into both air and water [90]. Among recovered fibers products, the tissue paper manufacturing process generates the highest amount of waste (10 times more than packaging paper) [91]. During the recycling of 1 ton of wastepaper for papermaking, approximately 300 kg of RPS is generated. This constitutes most of the generated waste from paper production and recycling, contributing up to 28.4% of waste per unit of produced paper [92,93].

A typical process for water treatment in a P&P mill involves primary treatment to eliminate suspended solids, followed by secondary treatment. The resulting solid residue obtained after thickening is called primary sludge (PS) and is generated in significant quantities. It is reported that one ton of paper yields approximately 30 kg of PS [94]. The composition of PS includes organic matter, nitrogen, phosphorus, paper fillers, low biodegradable organic matter (mainly cellulose), and it possesses a high C/N ratio (150 to 250) [95]. The primary sludge is further treated for the stabilization of organic matter by destructing pathogens and reducing volatile substances. This treatment is aimed at improving the quality of effluent for safer disposal. As preparation, the PS is sometimes neutralized to a pH of 6.5 to 8.5, suitable for biological treatments, by adding acid or alkali. Then, biological treatment is applied using oxygen-consuming (aerobic) microorganisms for the conversion of soluble organic matter into CO_2 and water for biochemical oxygen demand (BOD) reduction [96]. Most of the biological effluent treatment plants towards secondary sludge in the P&P industry employ activated sludge systems [97,98], yet some variations of these systems include filters and sequence reactors such as moving bed biofilm reactors (MBBRs) and membrane bioreactors (MBRs). Sometimes, anaerobic treatment is used, followed by an aerobic biological one [36,99,100]. The treated waste then flows into a coagulative precipitation clarifier, with coagulation agents, to remove colloidal particles such as lignin and paper fillers. Depending on its purity level, the effluent water from this process can be reused within the mill or released into the environment.

The secondary paper sludge (SPS) that is precipitated in the clarifier is extracted as solid content at a concentration of approximately 3%, directed to a dehydrator, and de-watered to reach a solid content of 40–60% [92]. SPS is considerably more difficult to de-water compared to primary sludge. Therefore, most pulp and paper facilities opt to de-water a mixture of primary and secondary sludge. The primary organic components of the secondary paper sludge are microbial extracellular polymeric substances (EPSs), non-biodegradable materials, and microbial cell biomass [100]. Additionally, it contains a higher amount of nutrients than primary sludge and maintain a low C/N ratio (from 5 to 30) [95].

Due to the organic content, the landfilled paper mill sludge is subject to aerobic and anaerobic decay. Theoretically, when landfilling 1 ton of low-ash paper mill sludge (<30% ash), approximately 2.69 tons of CO_2 and 0.24 tons of CH_4 are released into the environment [101]. SPS volumes are lower than those corresponding to the PS, since most of the heavy, fibrous, or inorganic solids are removed in the primary clarifier. In addition, SPS has a higher content of lignin and nitrogen, as well as kaolin, calcium, and other fillers, vs. PS [100]. In most mills, PS and SPS are mixed to form a combined sludge, with a variety of SS:PS ratios [102].

An additional sludge stream is de-inking sludge, which is a combination of the viscous float or scum created by the dissolved air floatation in the ink removing process for recycled paper fibers and the primary and secondary clarification processes. This sludge stream

is usually characterized by a high C:N ratio explained by the high organic content of wastepaper.

Paper mill sludge is one of the last materials in the waste treatment chain, with costs up to 60% of the total wastewater treatment plant coast [101,102]. Some of the de-watered products are effectively used as soil conditioner and other applications, but most of them are currently incinerated in sludge incinerators [103] or landfilled [100,104], disposal practices that are unfavorable ecologically and economically.

4. CE Aspects of Paper Manufacturing and Bioethanol Production

4.1. CE in Pulp and Paper Mills

As businesses and bureaucracies increasingly digitalize, paper mills must become more competitive by becoming more efficient. The paper industry also faces continuous demand to reduce harmful pollutants releases into water and air [105]. Publications from governmental institutions report that embracing a circular economy would bolster the EU's effort to achieve climate neutrality by 2050 [106]. Therefore, the P&P industry is motivated to convert its processes to circular economy systems, including feeding recycled paper into production [23]. One challenge is that, due to sanitary and other implications, less than 80% of paper can be recycled. Moreover, constructions such as beverage packaging, which includes plastic and aluminum, require additional setup of waste sorting [105]. In this respect, European mills are better positioned than competitors in less developed countries that do not have enough recycled paper to feed their paper mills. The paper recycling rate in Germany, for reference, is above 80%, while it is less than 30% in India [73,76]. The inadequate availability of indigenous wastepaper for papermaking in India is mainly attributed to the fact that, although most of the consumed paper is collected, it is used for multiple purposes such as wrapping and not solely for paper production. 95% of the wastepaper collection system is in the hands of the unorganized sector, and there is no legislation that could promote resource recycling [52]. As China, and gradually other Asian countries, have increasingly restricted the import of recovered fiber (as well as other recovered materials), the dynamics have shifted. While prices of old corrugated containers (OCCs) and other papers for recycling have plummeted in North America and Europe, prices of domestic Chinese OCCs have risen drastically, challenging both the price and availability of recycled-based corrugated board [18].

With the growing needs worldwide, it appears that the collection of yesterday's consumption is not sufficient for tomorrows' manufacturing. Research is being conducted to improve that ratio. For example, banning toxic inks as an increasing factor in the value of paper recovery is being investigated [53]. A case study of CE in the papermaking industry is the CE papermaking park in China, which piloted a governmental program of advanced CE. Instead of local energy supply that is inefficient for each manufacturer alone, the essence of this park is the centralization of power and heat supply, water supply, solid waste treatment, and wastewater treatment for many papermaking plants together. Energy recycling from the steam line is utilized for cooling water or heat. Solid waste such as paper and de-inking sludge is recovered to produce bobbin paper, which is used for reel cores production. Paper sludge can also be used together with coal in combustion for power supply due to its high calorific value of about 1500 kJ/kg. Environmentally, this method raises a challenge of ash generation, which requires a proper solution such as use in the cement industry [107]. Other studies demonstrate the crucial role of policymakers in the implementation of CE aspects in the forest-wood sector. For example, the forest-wood sector suffers from regulatory inconsistencies like subsidies for wood-waste incineration practices, which act in contrast to the need for incentives for upcycling and reuse practices [108].

Paper sludge originates from the waste stream, which can be dealt with following various CE guidelines and benchmarks [109]. The potential utilization of wastewater in paper mills as a resource for process refeeding has been supported by calculations [8]. However, the challenge lies in achieving a complete system closure and effluent reutilization in kraft mills, as prolonged zero discharge operation often leads to issues like corrosion

from chlorides and sulfur [29]. Closing the water circuit, while beneficial in reducing freshwater consumption, poses challenges such as odor, increased slime generation, and process complexity. Some German paper mills have successfully implemented almost fully closed-loop water systems, enjoying location flexibility, reduced wastewater discharge fees, and process benefits such as higher solid content of the paper and drying energy reduction [11]. Membrane technology, particularly membrane filtration, emerges as a solution for closing the water loop in paper mills. While direct membrane treatment can minimize organic matter, a combined approach with biological treatment is preferred for effective water cleaning and cost savings [35]. Examples include the Eltmann newsprint mill using nanofiltration (NF) and a Canadian pulp mill employing reverse osmosis (RO) to purify wastewater for bleaching [98,110]. However, membrane fouling necessitates pre-treatments like pH adjustment and complementary measures like ozone treatment [111]. The circularity-impeding process of membrane cleaning involves backwash, chemical cleaning, and energy-consuming ultrasonic cleaning [112].

4.2. CE Indicators

The imperative to achieve circularity in the Circular Economy (CE) has heightened the significance of production scale, conferring exponential benefits upon large-scale enterprises. There is an unmistakable trend towards the emergence of dominant market players in the CE, with the potential for these market leaders to acquire other companies in an economic and environmentally conscious environment, potentially resulting in monopolistic situations [113]. Decision-making for converting processes to CE or expanding to other related businesses requires reliable indicators for financial and environmental parameters. CE efficiency indicators and monitors are difficult to establish and agree upon in the paper industry, among other industries, especially when addressing the European objectives of CE [114]. Businesses find it challenging to present remedies for issues arising from CE due to the shortage of indicators and targets. This limitation arises from a lack of understanding about the alternatives generated by CE and its economic advantages, given that it constitutes a nascent scientific field of study. Commonly utilized indicators for macro-level evaluations in CE include those based on material flow analysis (MFA). At the micro-level, the Ellen MacArthur Foundation and Granta Design's material circularity indicator (MCI) are widely regarded, offering insights into material circulation within a product, measuring linear and restorative flows, as well as providing information on product utility; however, it does not comprehensively convey the sustainability of the product [115]. Sanchez-Ortiz et al. [116] had listed indicators for aspects of the CE that can influence the micro and macro industrial environment and require various levels of data input. For example, an indicator can be considered by the wastewater treatment method and sludge creation [109,114]. Based on the characterization of water and sludge flows, reductive and productive indicators of CE can be calculated for sludge and for wastewater. These parameters present the percentage of recover sludge and the potential of water consumption reduction [114]. However, they cannot stand alone and must be accompanied by environmental effects and cost savings in the specific plant location. CE evaluation also depends on the production system, having closed and open production systems, which differ in their autonomy from or dependence on the external environment, with open supply chains creating value throughout interconnected networks, revaluing waste flows as resources [117].

5. RPS for Energy Applications

5.1. Waste-to-Energy (WtE)

Another category of paper mill sludge (PMS) management is waste-to-energy (WtE), which groups several methods [96]. Thermal processes, like pyrolysis, provide an option for thermally upgrading the PMS to higher calorific value fuels. The bio-oils and charcoal produced from paper sludge pyrolysis have the potential to provide marketable feedstock and sources of energy. Charcoal derived from biomass was traditionally used as metallur-

gical fuel and is also being considered as a soil amendment and fertilizer replacement. The bio-gas product of waste pyrolysis has sufficient calorific energy and can be combusted to provide the required internal heat of pyrolysis, thus closing the circular process and reducing the external heat supply [91,118]. Other thermal processes include combustion incineration, steam reforming, wet oxidation, gasification, and more [99].

5.2. Bioethanol Production from Lignocellulosic Biomass

Ethanol (or EtOH, C_2H_6O) is a colorless liquid with a slight odor, soluble in water, flammable, and volatile. Ethanol, unlike fossil fuels, is a renewable energy source produced through the fermentation of sugars. As a high-octane fuel (98), it has replaced lead as an octane enhancer in petrol. Blending ethanol with gasoline fuel benefits the engine, burns more completely, and reduces polluting emissions [119]. Ethanol can also be used as a fuel for power generation, such as in solid oxide fuel cells, and as an ingredient in the chemicals industry [120,121].

Bioethanol is produced from natural matter. first-generation bioethanol feedstock is mainly edible food crops such as rice, corn, sugarcane, and vegetable oils like soybean oil and olive oil. Production of first-generation bioethanol has its disadvantages, competing with the food supply and land utilization. However, this form of biofuel is commercially available and known for its yield and production process [14].

Second-generation bioethanol refers to ethanol produced from nonedible feedstocks such as woody biomass, herbaceous biomass, solid waste, and animal fat. Compared to the first generation, the amount of energy that can be produced per land area is much bigger. Some drawbacks, however, are higher capital costs in production due to sophisticated processing equipment and lower energy density vs. first-generation bioethanol [122].

The conversion of lignocellulosic biomass into bioethanol generally starts with feedstock preparation that involves cleaning and size reduction. This is done by milling, grinding, or chopping and is crucial for the removal of impurities and increasing surface area; however, this step is energy-consuming [123]. The process is followed by four steps: pretreatment for the degradation of the lignocellulosic matrix, hydrolysis of cellulose in the lignocellulosic materials to fermentable reducing sugars, fermentation of the sugars to ethanol, and lastly, distillation and recovery of the produced ethanol (Figure 5).

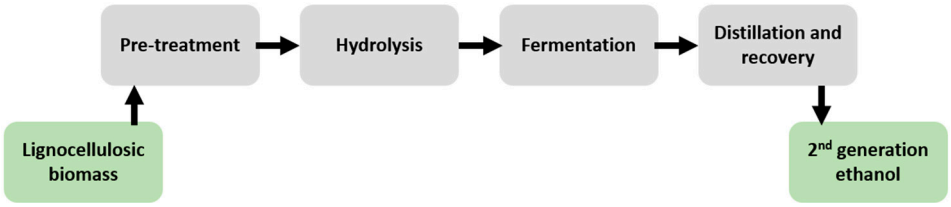


Figure 5. Stages in second-generation bioethanol production.

Pre-treatment is needed to reduce the lignin and hemicellulose amount, as they hinder hydrolysis by impeding the access of cellulase enzymes to cellulose [124,125]. The pretreatment should also reduce cellulose crystallinity and increase its porosity or surface area, which can significantly improve hydrolysis. In addition to being cost-effective, it is required to prevent the loss of carbohydrates and the formation of hydrolysis-inhibiting by-products [126,127]. This process has been intensively studied as it is a major technical and economical bottleneck in the bioconversion of lignocellulos to bioethanol, accounting for 40% of total costs [128], hence enabling scaling up production [129,130]. During pretreatment, inhibitory compound may be generated. These compounds have a negative effect on enzymes and microorganisms, affecting catalytic processes and reducing ethanol production yield. Table 5 presents current industrial pre-treatment methods.

Table 5. Current industrial pre-treatment methods, adapted from [11,131,132].

Pre-Treatment Method	Advantages	Disadvantages
Steam explosion	• Allows lignin transformation and hemicellulose solubilization. • Cost-effective.	• Partial hemicellulose Degradation. • Formation of toxic Compounds. • Requires high pressure and temperature.
Ozonolysis	• Reduces lignin content. • No generation of toxic compounds.	• High costs and energy demand. • Requires high amount of ozone.
Ammonia fiber Explosion	• Minimal formation of inhibitors. • Requires low temperature. • Increases accessible surface area.	• Not suitable for softwood. • Not efficient for raw materials with high lignin content. • Requires large amount of ammonia. • High costs.
Organosolv	• Promotes lignin and hemicellulose hydrolysis.	• Solvents need to be recycled. • High costs. • High toxicity.
Concentrated acid	• Requires ambient/low temperatures. • High glucose yield.	• High cost of acid. • Requires recovery of acids. • Reactor corrosion. • Formation of inhibitors.
Diluted acid	• Removal of hemicellulose and part lignin. • Less formation of inhibitors. • Less corrosion problems.	• Generation of degradation products. • Production of low sugar concentration.

Hydrolysis is usually catalyzed by cellulase enzymes, and fermentation is carried out by yeast or bacteria. Factors that have been identified to affect the hydrolysis of cellulose include the porosity (accessible surface area) of the feedstock, cellulose fiber crystallinity, and lignin and hemicellulose content [10].

Ethanol is produced by fermenting soluble sugars using a variety of microorganisms. The fermentation is conducted in anaerobic conditions, with the maximum theoretical yield being 0.51 kg of ethanol and 0.49 kg of CO_2 per kg of glucose [133]. There are several possibilities for the integration of hydrolysis and fermentation steps. These include separate hydrolysis and fermentation (SHF), simultaneous saccharification and fermentation (SSF), and consolidated bioprocessing (CBP) [134]. SHF consists of two separate hydrolysis and fermentation steps. In SSF, both steps are conducted simultaneously in the same vessel. In this method, soluble sugars are immediately fermented into ethanol, improving both enzymatic hydrolysis efficiency and ethanol yield. In CBP, enzymes are produced alongside hydrolysis and fermentation in a single step [22].

Generally, at the end of the fermentation step, the bioethanol value stands at 5% wt. This is a lower value compared to first-generation ethanol, which stands at 12% wt. The ethanol broth is distilled in a stripper column to reach a 20% wt. concentration and then further concentrated in a rectifier column to no higher than 95.6% wt. ethanol in water.

Distillation is an energy-demanding step, accounting for 60–80% of the total separation cost of bioethanol from water [22].

5.3. Paper Wastes as a Lignocellulosic Material

Paper wastes are considered a good lignocellulosic biomass source for bioethanol production because of their high cellulose content (Table 6). Paper is usually recycled 3–4 times [135], and after that, most fibers become too short and incompatible for papermaking. Using such fibers may negatively affect paper product properties; therefore, they are rejected as waste. Since the recovery of recycled paper cannot solely be in the papermaking market, RPS may also be used for ethanol production, as the process waste is beneficial [136].

Table 6. Paper sources' composition.

Source	Cellulose	Hemicellulose	Lignin	References
Newspaper	40–69	25–40	18–30	[137–139]
Kraft paper	57.3	9.9	20.8	[134]
Corrugated cardboard	53–57	10–13	21–22	[137]
Office and copy paper	57–63	16–21	0–6.5	[137,139]
Paper towel	53	13	18	[137]
Paperboard SBB [a]	64	20	5	[137]
Paperboard SUB [b]	43	12.5	24.3	[137]
Bleached softwood kraft pulp	82	16	0.6	[140,141]
Bleached hardwood kraft pulp	70–81	17–27	0.8–3	[140,141]
Unbleached kraft pulp	72	20	3–7	[142,143]
Chemi-thermomechanical pulp (CTM)	54	25	19–21	[140,141]
Municipal solid waste (MSW)	15	10	8.5–15	[144,145]
Waste paper	40–80	5–20	1–10	[138,146,147]
Paperboard mill sludge (PMS)	23.4–37	8.6–33	16.5–24.5	[141,148,149]

[a] SBB, solid bleached board; [b] SUB, solid unbleached board.

Both RPS and other PMS may have a negative cost impact from a circular economy standpoint, as they are an environmental burden and typically landfilled by default. PMS and RPS were evaluated and demonstrated as bioethanol feedstock, presenting successful conversion (Table 7). The integral utilization of lignocellulosic biomass, namely paper sludge, has been considered within the bio-refinery concept and can be evaluated by circular economy monitors for environmental, economic, and even social aspects. The common evaluation methodology is the life cycle assessment (LCA), standardized in the ISO 14040 series [142].

Table 7. Paper products and paper waste conversion to ethanol.

Lignocellulosic Source	Pre-Treatment	Ethanol Yield (L/Dry Ton Feedstock)	References
Recycled paper sludge (RPS)	Ozonation	120	[5]
Recycled paper sludge (RPS)	Sterilization (autoclaving with Sodium Azide)	93–112	[63]
Copy paper	None	287	[147]
Copier paper	None	198	[150]
Virgin pulp PS	None	241	[151]
Corrugated recycle PS	None	214	[151]
Newspaper	Oxidative lime: 1.875% *w*/*w* Ca(OH), 7.1 bar (absolute) O_2, 140 °C, 3 h	290	[152]
Office paper	Diluted acid: 0.5% *w*/*w* H_2SO_4, 220 °C	419	[153]
Recycled paper sludge (RPS)	Ash removal (TAPPI, 1995)	289–332	[6,154]
Waste office paper	Diluted acid: 1% *v*/*v* H_2SO_4, 50 °C, 3 h	206	[155]

5.4. Paper Sludge as a Source of Ethanol

Several PS valorization routes have already been suggested and explored. Many different products have already been produced from sludge, including: nanocellulose [59], lactic acid [156], cellulase [8], isoprene [157], microbial lipids [158], and building materials supplement [159]. In addition, various WtE routes have also been suggested for a variety of energy products, including: hydrogen [160], bio-gas from anaerobic digestion (AD) [161], butanol through acetone-butanol-ethanol fermentation [162], bio-oil [163], bio-methanol through gasification [164], and bioethanol. These solutions have yet to be found sustainable, resulting in PS being landfilled for the most part. The conversion of sludge to ethanol holds several economic benefits, and even negative costs, since using PS to produce other products reduces landfilling and shipping costs, environmental fees, and eliminates purchasing costs without the need to purchase the original source material. In addition, other by-products from the papermaking process, like kraft pulp and Spent sulfite liquor, have also been suggested for ethanol production, [22]. Table 8 shows different studies on bioethanol production from papermaking process waste by-products.

Table 8. Ethanol production from papermaking process waste by-products.

Raw Material	Ethanol Production (g/L)	Yield (%)	References
Recycled paper sludge	14.9	9.44	[5]
Recycled paper sludge	5.6–6.3	67.9–76.8	[63]
Virgin pulp sludge	34.2	66.9	[152]
Primary sludge	25–30	94.5–95.7	[165]
Primary sludge	30.7–58.8	90	[166]
Primary sludge	37.2	23.5	[167]
Kraft pulp	30–38	16.8–20.2	[7]
Kraft pulp	5.88	4.5	[168]
Kraft pulp	N/A	12–20	[169]
Spent sulfite liquor	8.1	49	[170]
Spent sulfite liquor	9	25	[171]

A large amount of water is required in the papermaking process for both the reaction media and for use as wash water. Depending on the type of raw material input and the process conditions, there is great variability in PS properties, such as organic content, ash content, and pH [22]. In addition, there is a large variation in the chemical composition of the PS produced in different pulp mills. Previous work showed differences in the chemical composition of 37 PS samples that originated from different mills, depending on the feed material and the upstream processing in papermaking [152].

Although PS shows great promise, a major barrier in PS conversion to ethanol is its high ash content. The ash, mostly $CaCO_3$, absorbs enzymes and increases sludge pH levels and suppresses enzymatic activity. Acidic treatments can be used for neutralization to minimize this limitation [172]. Moreover, high ash content limits the total solid load, eventually increasing processing costs. PS also has high water-holding capacity and viscosity, resulting in inefficient mixing and poor mass transfer [22].

5.5. Economic Aspects of CE in the Paper Industry

Paper waste management poses a major economic burden on paper and cardboard producers and recyclers. This burden has dramatically increased in recent years, due to the increase in e-commerce and shipments and the growing need for cardboard boxes and containers [59]. These challenges are also accompanied by major fluctuations in paper and cardboard prices, initially started by a major reduction of more than 300% in cardboard prices, due to the high-volume importation of cheap cardboard from China in recent years, which left the paper recycling sector "in a crisis situation" [173]. A more recent case study in Catalonia, Spain, showed a major drop of 73% in paper and cardboard prices from 74.5 €

to 20 € during 2018–2019 [174]. Recently, cardboard prices have been moving up, which is explained by the end of inventory hoarding that characterized the post-pandemic recovery. However, it is too soon to determine if these price increases will stay and be repeated [175].

Furthermore, the necessity for waste handling and shipments to landfills/treatment sites, as mostly practiced, contributes substantially to the economic burden of the paper industry. The necessity for the paper and carboard industry to shift toward a CE is demonstrated by the cost of unit cargo for truck shipments that can be estimated to range between 40–180 USD/ton of waste (for a 1000 km distance), according to the truck fullness ratio and additional tax fees [176]. A recent publication by the Ministry of Land, Infrastructure, Transport and Tourism of Japan issued a transportation rate of 7.63 USD/km for a 20-ton truck (with a volume capacity of 75 m^3) [177]. This has led to several works evaluating full life cycle assessments (LCAs) in the paper industry, analyzing water and raw materials and end waste-products for the possibility of further use, thus increasing economic feasibility [60,178,179]. Moreover, PS valorization into valuable energy products holds high potential for environmental benefits. A case study conducted on a virgin pulp mill has shown that the use of PS bioenergy for ethanol and bio-gas production has the potential to reduce energy demand by 10%, while reclaiming 82% of the water from the PS. As a result, greenhouse gas emissions (GHGs) will be reduced by three times, and solids suitable for land spreading will be produced as well [180]. To date, carbon taxes and emissions trading system (ETSs) cover 20% of global emissions. Since these tools increasingly take central places in GHG emissions regulations, this approach can be much more beneficial economically, saving high carbon fees [181].

Integration of ethanol production may transform P&P mills into biorefineries, allowing them to diversify production and increase profitability. For example, several works have assessed the techno-economic potential for repurposing kraft mills into ethanol production plants [182,183]. Although sulfite pulps correspond to only 2% of annual wood pulps [22], additional papers have suggested the conversion of sulfite mills into integrated biorefineries [184,185]. Bioethanol production integration into existing paper mills can maximize the use of raw material and reduce operational costs. The economics for the conversion of PS to ethanol in kraft pulping mills were evaluated to be a low-cost opportunity, due to the negative cost of feedstock material and the simplicity of the process [186]. Nevertheless, industrial-scale production of ethanol from PS and from lignocellulosic material is limited due to high capital investment and technical risks [22].

6. Conclusions and Future Directions

This paper has viewed various aspects of circularity concepts in the ethanol production process from paper mill sludge, emphasizing the importance of integrating waste-to-energy strategies.

Adopting circular economy concepts in the papermaking industry represents a promising and sustainable solution for increasing resource efficiency and addressing environmental challenges. The valorization of paper sludge for energy production, i.e., ethanol, reduces waste disposal while diversifying feedstock material. Having the paper mill treat its sludge towards bioethanol production by leveraging its existing processes enhances circularity and increases the entire system's economic efficiency. The circular economy model allows closing the loop in the P&P industry and transforming a waste product into a valuable resource. Among the additional environmental and economic benefits of circular economy in ethanol production is the minimization of the carbon footprint, reduction in resource use, supply chain diversity, and higher resilience to feedstock market fluctuations.

In conclusion, applying circularity principles to the production of ethanol from paper sludge can establish a viable ethanol production model that not only addresses environmental concerns but also poses great potential for economic contribution. Implementing circularity in industrial processes is crucial for achieving a sustainable balance between economic prosperity and addressing environmental concerns.

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