



Environmental and economic analysis of the transformation of paper mill sludge treatment technologies in China

Yanfei Lin¹ · Guoxia Wei² · Hanqiao Liu¹ · Kai Li¹ · Yuwen Zhu¹ · Qianlong Han¹ · Yunzhen Yang¹ · Yi Lian³

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Abstract

Paper mill sludge (PMS) is featured with a high content of cellulose and hemicellulose, and using its characteristics to make paperboard can achieve a high-value utilization of PMS, which has attracted growing interest. In this study, currently prevalent landfill, incineration technologies (generating heat and electricity by incineration), and three paperboard technologies (medium density fiberboard, pulp board, and corrugated paper) were evaluated and compared via life cycle assessment (LCA) and life cycle costing (LCC) methods. LCA results show that the PMS-to-pulp board outperforms others with an energy conservation and emission reduction (ECER) value of -2.86×10^{-8} , while the landfill exhibits the highest overall environmental impact with an ECER value of 4.80×10^{-9} . LCC results reveal that the PMS-to-pulp board delivers the highest economic profit with \$257.357, while the landfill is the lowest with \$-35.63. The PMS paperboard technologies are more economically friendly than the incineration technologies due to additional electricity/steam consumption during the PMS pre-drying process in incineration. In addition, different scenarios were set up to explore national GHG emission reduction potential by increasing paperboard technologies application rate and reducing the proportion of landfill and incineration. The scenario analysis suggests that replacing 90% of landfill and incineration ratio with PMS paperboard technologies could tremendously improve the overall emission reduction performance with -9.08×10^{10} kg CO₂ eq. This result indicates that the PMS treatment technology transformation has a significant favorable impact on the achievement of the “carbon neutrality” target.

Keywords Paper mill sludge · High-value utilization · Life cycle assessment · Life cycle costing · GHG emission reduction

Abbreviations

PMS	Paper mill sludge
MDF	Medium density fiberboard
LCA	Life cycle assessment
LCC	Life cycle costing
LCI	Life cycle inventory
CLCD	Chinese life cycle database
ECER	Energy conservation and emission reduction
GHG	Greenhouse gas

Introduction

Paper mill sludge (PMS) is a solid waste generated during the wastewater treatment process in the paper manufacturing industry discharging 32 million tonnes in China by 2021 (China Statistical Yearbook 2021), of which 70% is primary sludge and 30% is secondary sludge (Zambare and Christopher 2020). PMS contains organic pollutants in addition to cellulose, kaolin, and organic matter (De Azevedo et al. 2020), which can lead to a range of environmental and health problems if not properly handled (Pasciucco et al. 2023). The major PMS treatment technologies in China today include landfill and blending incineration for heat and power generation (Maheswaran et al. 2023). Nevertheless, landfill occupies substantial space, and causes secondary pollution of leachate or landfill gas, which is not conducive to the construction of “waste-free cities” (Chen et al. 2019). Sludge blending incineration reduces the cost of sludge treatment, but this option entails unacceptable environmental risks due to heavy metals, dioxins, and other pollutants in the flue

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✉ Yuwen Zhu
zhuyw@tcu.edu.cn

- ¹ College of Energy and Safety Engineering, Tianjin Chengjian University, Tianjin 300384, China
- ² College of Science, Tianjin Chengjian University, Tianjin 300384, China
- ³ Tianjin Urban Planning and Design Institute Co, Ltd, Tianjin 300000, China

gas that are released into the atmosphere (De Azevedo et al. 2018). Thus, conventional PMS treatment technologies no longer meet the current green and low-carbon development requirements. Exploring less carbon emissions and economically beneficial and sustainable solutions for treating PMS is a point that deserves widespread attention.

PMS has a high organic matter content of 40~50%. The organic matter consists of crude protein, fibers, hemicellulose, and lignin, which is suitable for recycling as a raw material for the production of paperboard (Furlani and Maschio 2018). The PMS paperboard alternative technologies mainly include the production of medium-density fiberboard (MDF), pulp board, and corrugated paper, which are thriving in the context of “waste-free cities” in China. Primary and secondary PMS have natural bonding properties due to their fiber and protein content and can be used as a fiber source and particle binder in MDF production (Faubert et al. 2016). Pulp board or corrugated paper is mainly made from cotton fiber or waste paper, mixed with PMS and waste paper pulp. The MDF, pulp board, and corrugated paper produced from PMS have characteristics such as high strength, compression resistance, high abrasion resistance, and puncture resistance, which achieves high-value utilization of PMS. By implementing PMS resource utilization technologies, thereby reducing environmental burden, promoting a circular economy, and facilitating the coordinated development of economy, society, and environment, sustainable development goals 6, 9, 11, and 12 can be achieved. However, the environmental and economic benefits of these technologies are unclear and need to be quantified.

Life cycle assessment (LCA) and life cycle costing (LCC) are commonly used to evaluate the environmental impacts and economic benefits of sludge treatment technologies (Liu et al. 2022b, 2023). The production of pollutants, energy recovery, and environmental impact of the co-incineration of sewage sludge and biomass pellets was assessed by LCA. The result shows that sewage sludge incineration has the greatest impact on climate change, terrestrial ecotoxicity, and human toxicity (Jadlovec et al. 2023). Yang et al. (2023) demonstrated that the greenhouse gas (GHG) emissions associated with direct thermal drying combined with coal co-incineration incinerators are three times more than indirect thermal drying and self-sustaining combustion in China. The recycled papermaking industry based on domestic recovered paper and three alternatives (straw, imported deinked pulp, and imported wood pulp) as the raw materials were compared and analyzed via LCC (Li et al. 2020b). There are net reductions in GHG emissions (-1.43 t CO₂ eq./t dried sludge) for the PMS-to-biochar option relative to landfilling using LCA (Mohammadi et al. 2019). Numerous research focused on sewage sludge treatment, especially landfill and incineration technologies, but few studies performed PMS treatment technologies. Compared with sewage

sludge, PMS has a high content of cellulose and organic matter, which allows it to be utilized in the production of paperboard, with a huge resource recovery potential.

This paper aimed to assess the environmental impacts and economic benefits of the conventional landfill, blending incineration, and paperboard technologies based on the characteristics of PMS containing lignin and other organic substances. The six technologies were analyzed and compared from characterization and normalization through the LCA method, i.e., landfill, incineration technologies (generating heat and electricity by incineration), and three paperboard technologies (medium-density fiberboard, pulp board, and corrugated paper). In addition, based on total national PMS and current PMS treatment situation, multiple scenarios involving reducing landfill and blending incineration and increasing paperboard technologies' application rate were designed to explore GHG emission reduction potential from national-level PMS treatment. Furthermore, the economic costs were quantified via the LCC method from an economic perspective. The key factors of environmental and economic impacts of each technology were determined, and efficient measures were further suggested. The results can provide scientific insights into the transformation of PMS treatment technology in China.

Methodology

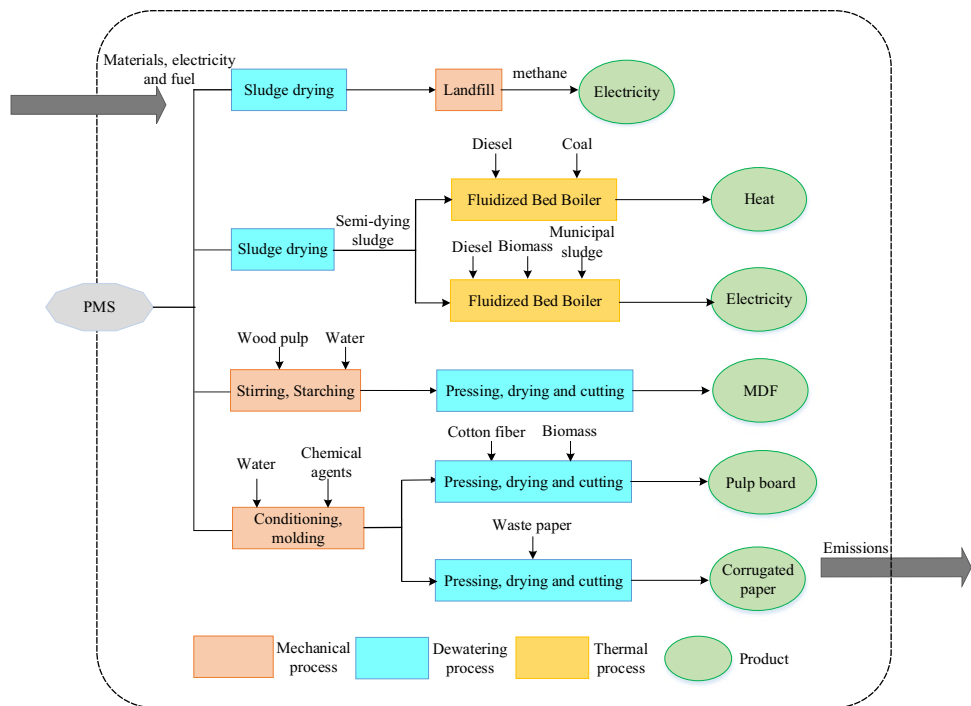
Goal and scope definition

The purpose of this study is to assess the environmental and economic performances of six PMS treatment technologies. For a fair comparison, the functional unit is defined as treating 1 tonne of dry PMS (0% moisture content). As shown in Fig. 1, the system boundary starts from the PMS entering the plant area to product production for each technology. Final products (i.e., heat, electricity, MDF, pulp board, and corrugated paper) produced in PMS utilization processes were considered to be complete substitutes for conventional and analogous merchandise on the market. The mechanical and chemical characterization of PMS in Asia are shown in Table S1. The characteristics of the PMS utilized by all technologies and their advantages and disadvantages are shown in Table S2.

Technology description

Baseline (landfill) The wet sludge is dried with steam to a moisture content of 40% and then sent to a domestic landfill, where the methane produced is used to generate electricity. Material and energy consumption mainly include electricity, steam, and lime.

Fig. 1 System boundaries of six technologies



PMS-to-heat Twenty-one percent of semi-drying PMS is mixed with coal and fed to the circulating fluidized bed boiler for cogeneration, combined heat and power; the PMS is dried to 40% moisture content using electricity. Energy and material consumption mainly include electricity, limestone, and water.

PMS-to-electricity Thirteen percent of semi-drying PMS is blended with biomass and municipal sludge and fed to the circulating fluidized bed boiler for power generation; the PMS is dried to 40% moisture content using turbine extraction steam. Material and energy consumption mainly include electricity, hydrated lime, and water.

PMS-to-MDF PMS is mixed with textile long fiber and waste pulp to produce pulp, which is compounded and pressed by a paperboard copying machine to obtain MDF. Raw materials and energy consumption mainly include water, steam, biomass, and electricity. The technology does not produce exhaust gas, and wastewater is all recycled.

PMS-to-pulp board The mixture of PMS, waste pulp, and cotton fiber is dried and cut to form the pulp board. Raw material and energy consumption mainly include biomass, electricity, and steam. Wastewater is the main pollution.

PMS-to-corrugated paper PMS, waste paper, and residual pulp are blended dried and cut as corrugated paper. Raw materials and energy consumption mainly include electricity, steam, water, and waste paper. Wastewater represents the primary pollution in the entire process.

Scenarios description

At present, most of the solid wastes generated by the paper industry are disposed of by landfill or incineration, and the former is more widely used (Liu et al. 2022a). In the context of the “Waste-Free Cities” plan and the “Carbon Neutrality/Peak” policy, there will be a shift towards more environmentally friendly and sustainable models of solid waste disposal technologies. The choice of PMS utilization technology in each region may have a significant impact on GHG emission outcomes in this region. Therefore, scenario analysis was designed to explore the GHG emission reductions of different PMS treatment strategies by reducing mixed incineration and landfill and increasing PMS resource utilization at the national level.

In scenario 1 (representing the current situation of national PMS treatment), 70% and 30% of PMS were landfilled and incinerated, respectively. In scenario 2, landfill and incineration were set at 40% and 30% of used technologies, respectively. The remaining 30% was composed of PMS-to-MDF, pulp board, and corrugated paper at 10%, 10%, and 10%, respectively. In scenario 3, landfill and incineration were decreased to 10% and 30%, respectively, with the remaining 60% being composed of PMS-to-MDF, pulp board, and corrugated paper on average, 20%, respectively. In scenario 4, landfill was decreased to 10% and incineration was completely replaced. The remaining 90% was composed of PMS-to-MDF, pulp board, and corrugated paper on average, 30%, respectively. GWP is an indicator of the effect of greenhouse gases on the temperature of the Earth’s

atmosphere, using CO₂ as the reference substance. In the scenario analysis, GWP is used as a measure indicator of the magnitude of GHG emissions. About 0.24 t of dry PMS is generated by producing 1 tonne paper. Due to the insufficient data on the amount of PMS in each province, the amount of PMS in each province is obtained by multiplying the paper production in each province with the amount of PMS generated by producing 1 tonne paper. Where the provincial paper production data comes from the *2021 China Paper Yearbook* and *the National Bureau of Statistics*, and finally the above data is scaled up to each province in the country to calculate the national GHG emission reduction.

Data source and life cycle inventory

A life cycle inventory (LCI) of baseline and five PMS treatment technologies was collected from field survey and the environmental impact assessment reports of enterprises in Jiangsu, Zhejiang, Jiangxi, and Guangdong provinces. The detailed data are shown in the Supplemental Information. The background data on water, electricity, fuels, LDPE, most raw materials, and products are taken from the China Life Cycle Database (CLCD) in the eFootprint platform (Han et al. 2024). Background data for polyacrylamide and insecticides are from the European Life Cycle Database; background data for cotton fiber, strengthening agent, surface adhesive, and sizing agent are from real scenario processes. A cut-off rule (1%) was adopted, and unavailable raw materials weighing less than 1% of the original waste were excluded (Li et al. 2023). The different PMS moisture contents and origins may pose an effect on the environmental and economic evaluation results. Therefore, each PMS from various locations requires a site-by-site assessment. To perform a competitive study, the origin and moisture content of PMS were harmonized (Liu et al. 2021).

Economic data on budget costs from its environmental impact assessment reports. Merchandise values were acquired from firms or the public sector and reflect their market values in 2022. The PMS disposal subsidy is taken as the average of 6 plants.

The life cycle of six technologies is 30 years. The discount rate is taken as 6%; the salvage rate and maintenance cost are taken as 5% and 3.5% of the equipment investment, respectively (Hong et al. 2013). And the equipment investment is 35% of the total investment. The calculations do not take into account the effects of price dynamics (e.g., increases in energy prices) and inflation (i.e., depreciation of money). In terms of management cost, the wage of workers is \$ (USD) 7280/year. The revenue is divided into revenue from resource recovery, commissioned PMS disposal fee, and product selling fee. The price of electricity comes from the environmental impact report, and the price of raw materials depends on the market price.

Environmental and economic evaluation

According to the *International Reference Life Cycle Data System* handbook to quantitatively evaluate environmental performance, LCA was undertaken by eFootprint software which is based on ISO14040 and 14,044, an online LCA software with a built-in Chinese Life Cycle Database (CLCD) (Zhao et al. 2022). In this study, we selected 19 characteristic indicators related to the possible environmental impact of technological projects (Guo et al. 2021; Cheng et al. 2022). Detailed information on environmental indicators can be found in Table S3. The impact assessment methods embedded in the eFootprint platform are used in this study, which are obtained from ReCiPe Midpoint (H) for IRP and POFP, CML (2002) for ADP, EP and AP, IMPACT 2002 + for RI, Centrum voor Milieuwetenschappen Leiden (CML) (2001) for ODP, USEtox for HT-non cancer, HT cancer and ET, and Intergovernmental Panel on Climate Change (2013) for GWP (Zhao et al. 2022). The total calorific value for primary energy (i.e., coal, petroleum, and natural gas) and the total water amount are directly used to denote the indicators PED and water use (WU). Impact categories PED, SO₂, NO_x, NH₃-N, COD, and IWU in characterization results are used to calculate the comprehensive index of energy conservation and emission reduction (ECER) of the 13th Five-Year Plan in the next normalization analysis (Liu et al. 2022b; Li et al. 2023). The life cycle processes of PMS utilization technologies cause resource depletion and contaminant emissions, which greatly impact the attainment of China's ECER policy goals (Guo et al. 2022). The traditional quantitative assessment depends on the subjective evaluation of experts and the absence of a quantitative evaluation, and there are conflicts between various environmental impact indicators (Havukainen et al. 2022). A holistic approach to evaluation is necessary to arrive at a unified singular indicator (Jiang et al. 2022). Thus, the quantitative national ECER policy targets were adopted in this study (Zhao et al. 2021a). According to the energy conservation and emission reduction policy objectives in *the 13th Five-Year Plan* and *the National Environmental Protection Plan*, the “reduction rate per unit of GDP during the 13th Five-Year Plan” corresponding to the policy objectives is calculated and the weighted value is obtained after taking the reciprocal value. ECER assessment indicator system includes seven indicators (i.e., CO₂, PED, IWU, NH₃-N, COD, NO_x, and SO₂), which are based on the Nation's 13th Five-Year Plan and the overall environmental impacts represented by the following calculation formula (Zhao et al. 2021b):

$$S = \sum_{i=1}^7 \frac{A_i}{T_i \times N_i} \quad (1)$$

where S stands for the ECER indicator value; A_i is each indicator of utilization technologies; T_i stands for each measurable policy target of ECER and N_i stands for the national total of each indicator in 2015.

The LCC method addresses the economics of the entire life cycle process, with typical costs including raw material supply, waste management, energy consumption, and labor costs (Shao et al. 2015). Detailed costs of energy consumption and raw materials are shown in the Supplementary Information. The formula for LCC is quoted from (Liu et al. 2022b):

$$LCC = C_0 - \sum_{t=0}^T I_i \times PV_{sum} + \sum_{t=0}^T O_i \times PV_{sum} + \sum_{t=0}^T M_i \times PV_{sum} + \sum_{t=0}^T R_i \times PV_{sum} - S \times PV \quad (2)$$

$$PV_{sum} = \frac{(1+r)^t - 1}{r + (1+r)^t} \quad (3)$$

$$PV = \frac{1}{(1+r)^t} \quad (4)$$

where C_0 represents the capital cost; I and O represent the operational income and operating cost, respectively; PV_{sum} represents value sum; M represents the maintenance cost; R represents the management cost; PV is the discount factor; and T is the full life cycle. The analysis period for this study was set at 30 years. r is the discount rate, which is taken 6%. S is the salvage value. Positive values represent expenses, and negative values represent income.

Sensitivity analysis and uncertainty analysis

Sensitivity analysis and uncertainty analysis are important components of LCA to check the sensitivity and uncertainty of LCI input data results, where sensitivity can be calculated based on percentage adjustment limits for output and input parameters (ISO 14044, 2006; ISO 14040, 2006). Sensitivity analysis was performed using a one-time method in which the material input is varied by 5% (Wang et al. 2018), and uncertainty analysis reflects the absolute value of data dispersion by the ratio of the standard deviation of the raw data to the mean of the raw data, i.e., the coefficient of variation (CV) (Gong et al. 2022).

Results

Environment analysis results

The characterization results of the baseline and five utilization technologies are shown in Table 1. Positive values

indicate adverse effects, while negative values indicate beneficial effects. PMS-to-pulp board technology achieved environmental savings in all impact categories, followed by PMS-to-corrugated paper and PMS-to-MDF, with environmental benefits in 15–18 out of the 19 categories. The baseline resulted in the worst option.

Process cumulative contribution analysis

The contribution analysis of the baseline and five utilization technologies are shown in Fig. 2. For the baseline, steam, power consumption, lime, and power generation are the major contributors to most categories. For PMS-to-heat, heat and power generation are major contributors to most categories; direct emissions from the PMS incineration process include acidic gases (e.g., SO_2 , NO_x), CO_2 , and particulate matters, contributing significantly to AP, SO_2 , and CO_2 . For PMS-to-electricity, direct emissions and power generation are the primary contributors in the majority of categories. In the process of power generation production, the direct emissions of fossil fuel incineration include carbon dioxide, acidic gas, particulate matter, and nitrogen oxide, which make significant impacts on AP, RI, and EP. PMS co-incineration with coal or biomass fuel has the potential to offset greenhouse gas emissions as it replaces fossil fuel to produce heat and electricity (Goel and Kalamdhad 2017).

For PMS-to-MDF, MDF product, PAM, and power consumption contribute significantly to most indicators. The contribution proportion of PAM to ODP, ET, and NH_3-N for PMS-to-MDF reaches 32.74%, 43.91%, and 79.31%, respectively, which was mainly used as reinforcing agent, showing obvious environmental burdens. Thus, the use of PAM should be reduced or replaced with other environmentally friendly agents. For the PMS-to-pulp board, the pulp board makes a great contribution (over 80%) to most indicators. Steam is supplied by coal-fired boilers, and the mining and incineration of coal have a detrimental effect on GWP, WU, RI, and IWU. For PMS-to-corrugated paper, waste paper is the second largest contributor to environmental impacts, which has a significant positive impact on the environment because of the rational use of waste paper.

Normalization analysis

Normalization analysis is useful to uncover the effect of selected technologies on the overall regional environment and identify the factors that are normalized through statistical investigation (van Hijfte et al. 2023). The normalization results of the baseline and five utilization technologies are shown in the Supplemental Information and Fig. 3. For the baseline, steam and power consumption contribute significantly to most environmental indicators. Steam used in the drying process is the greatest contributor to PED, CO_2 , SO_2 , and NO_x , which

Table 1 Characterization results of the baseline and five utilization technologies

Impact categories	Unit	Baseline	PMS-to-heat	PMS-to-electricity	PMS-to-MDF	PMS-to-pulp board	PMS-to-corrugated paper
GWP	kg CO ₂ eq	3.27E+03	-6.75E+02	-8.98E+02	-3.51E+02	-8.73E+03	-1.29E+03
PED	MJ	2.80E+04	-9.76E+03	-2.45E+04	-3.19E+04	-1.77E+05	-2.52E+04
WU	kg	7.35E+03	1.80E+03	1.22E+04	-7.93E+04	-6.40E+03	-1.05E+03
AP	kg SO ₂ eq	8.53E+00	-2.86E-01	3.31E-01	-3.39E+00	-5.21E+01	-7.07E+00
ADP	kg antimony eq	1.28E-03	-6.81E-03	-5.63E-02	-5.83E-02	-8.59E-01	-1.07E-01
EP	kg PO ₄ ³⁻ eq	5.80E-01	-1.02E-02	-4.45E+00	-3.65E-01	-3.10E+01	-4.41E+00
RI	kg PM _{2.5} eq	9.29E+00	-1.94E+00	4.95E-01	-4.44E-01	-6.07E+00	-1.34E+00
ODP	kg CFC-11 eq	3.87E-06	1.03E-06	-2.73E-05	-1.44E-06	-8.40E-04	-1.20E-04
POFP	kg NMVOC eq	1.11E+00	6.48E-03	-1.54E+00	-5.10E-01	-2.78E+01	-3.88E+00
IRP	kg U235 eq	1.39E+01	1.76E+00	-2.45E+01	-6.41E+00	-1.36E+03	-2.01E+02
ET	CTUe	3.71E+00	-1.88E+00	-9.82E+02	3.25E+01	-1.44E+04	-1.57E+03
HT-cancer	CTUh	2.01E-07	-1.24E-06	9.19E-06	-1.12E-07	-5.86E-05	-8.16E-06
HT-non cancer	CTUh	3.57E-06	-1.51E-04	1.34E-03	2.00E-06	-5.65E-04	-7.85E-05
SO ₂	kg	5.31E+00	-7.07E-04	-1.76E+00	-8.40E-01	-3.45E+01	-4.93E+00
CO ₂	kg	2.41E+03	-6.21E+02	-6.83E+02	-3.09E+02	-7.75E+03	-1.15E+03
NO _x	kg	4.33E+00	-6.71E-01	-1.65E-01	-8.91E-01	-1.90E+01	-2.82E+00
NH ₃ -N	kg	3.11E-03	4.65E-03	2.69E-02	1.55E-01	-1.62E-01	3.43E-01
COD	kg	1.96E-01	-6.88E-02	-1.81E-01	4.36E-01	-4.93E+01	-8.15E+00
IWU	kg	7.34E+03	1.80E+03	1.24E+04	-7.93E+04	-5.99E+03	-1.05E+03

poses a serious environmental burden. For PMS-to-heat, coal contributes significantly to PED with a value larger than other materials and direct emissions. Power and heat generation display a large proportion of PED, CO₂, SO₂, and NO_x since they have significant beneficial impacts. For PMS-to-electricity, in terms of SO₂ and NO_x, direct emissions pose a serious environmental burden with values of 2.04×10^{-10} and 3.08×10^{-10} , which are the top two in the graph.

For PMS-to-MDF, the product shows the greatest detrimental effects for most categories apart from COD and NH₃-N. PAM contributes the largest negative impact to NH₃-N with the value of 9.01×10^{-11} because of the heavy environmental burdens caused by the production process. For PMS-to-pulp board and corrugated paper, the product has the greatest detrimental effects for categories except for IWU and NH₃-N, and steam used to dry the product exhibits the second largest contributions to SO₂, PED, NO_x, and CO₂.

Figure 4 displays that the values of PED, CO₂, COD, SO₂, and NO_x from the PMS-to-pulp board are much higher than other technologies with a value of -1.41×10^{-9} , -8.47×10^{-10} , -2.22×10^{-9} , -1.86×10^{-9} , and -1.03×10^{-9} , respectively. This shows that the environmental benefits of the PMS-to-pulp board are the highest. The value of IWU from PMS-to-MDF is much higher than other technologies due to the large water demand for urea. Overall, the PMS-to-pulp board is the most environmentally friendly of all technologies.

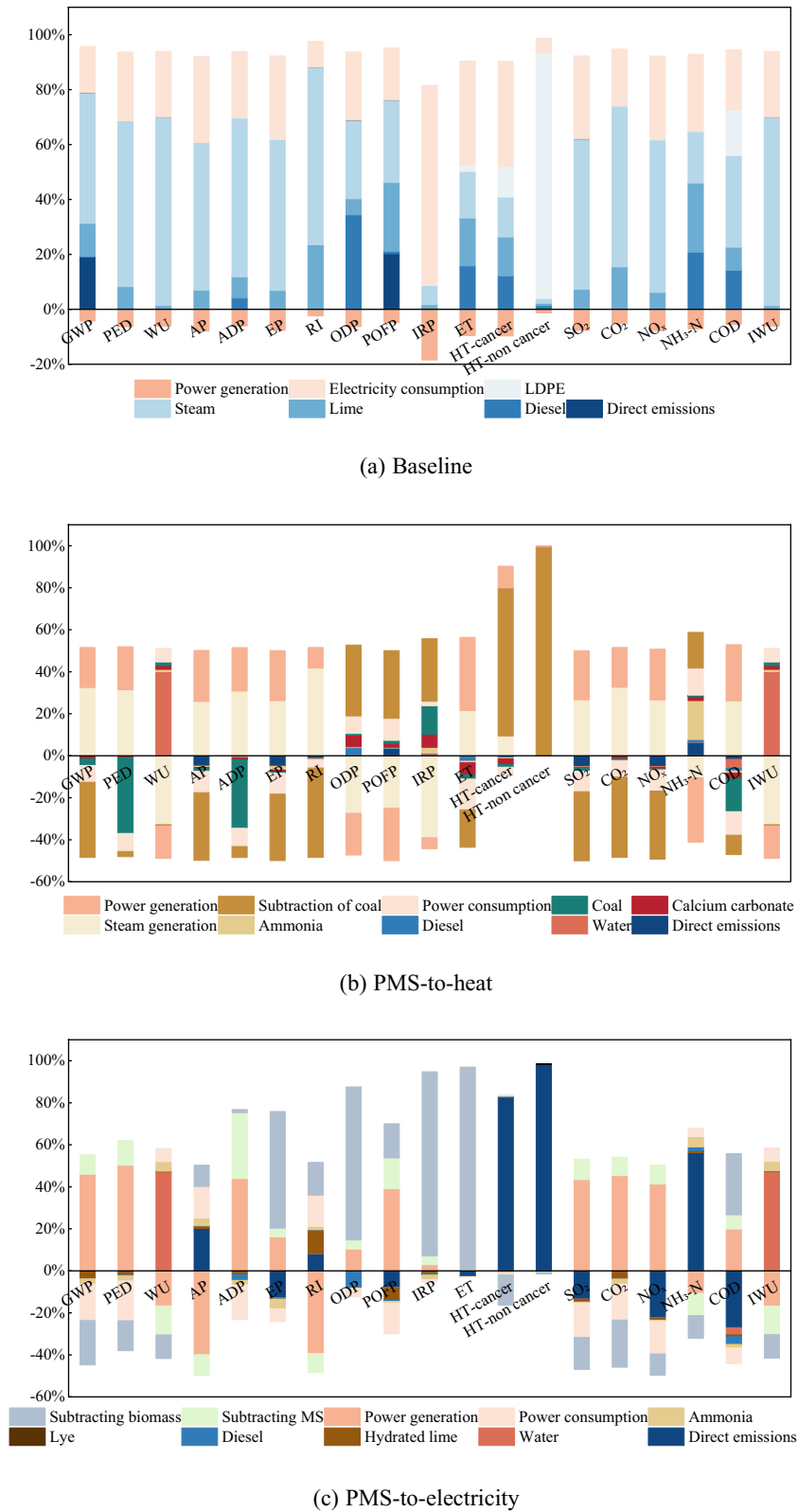
Energy conservation and emission reduction assessment

The ECER assessment results of baseline, PMS-to-heat, electricity, MDF, pulp board, and corrugated paper are shown in Fig. S1. For PMS-to-heat, the ranks of ECER results from highest to lowest are electricity generation, heat generation, diesel, and ammonia. In PMS-to-electricity, the ranks of ECER results are power generation, lye, diesel, hydrated lime, and ammonia, which is similar to the findings derived by Liu et al. (2023c). For PMS-to-MDF, pulp board, and corrugated paper, the product leads to significant impacts on ECER value. The ECER values of baseline, PMS-to-heat, electricity, MDF, pulp board, and corrugated paper are 4.80×10^{-9} , -9.34×10^{-10} , -1.57×10^{-9} , -4.46×10^{-9} , -2.86×10^{-8} , and -3.8×10^{-9} , respectively. The environmental benefit of the PMS-to-pulp board is preferably 30.6 times of PMS-to-heat, 18.2 times of PMS-to-electricity, 6.4 times of PMS-to-MDF, and 7.5 times of PMS-to-corrugated paper, while the baseline causes an environmental burden.

Sensitivity analysis

The results of the sensitivity analysis for each material and energy consumption of baseline and five PMS treatment technologies are presented in Fig. S2. A 5% variation in each factor of six technologies was conducted for sensitivity analysis. For the baseline, steam makes a great

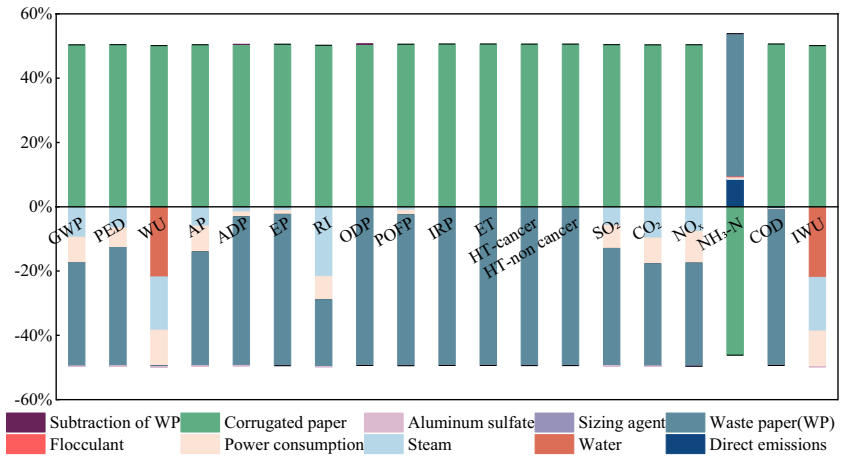
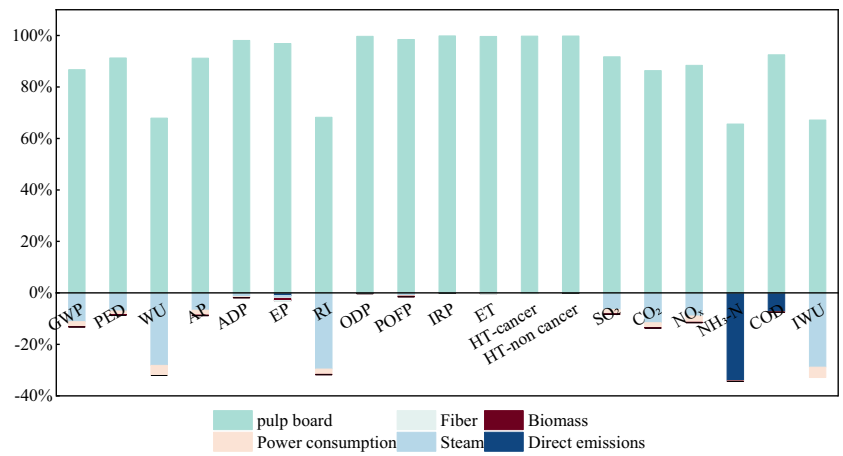
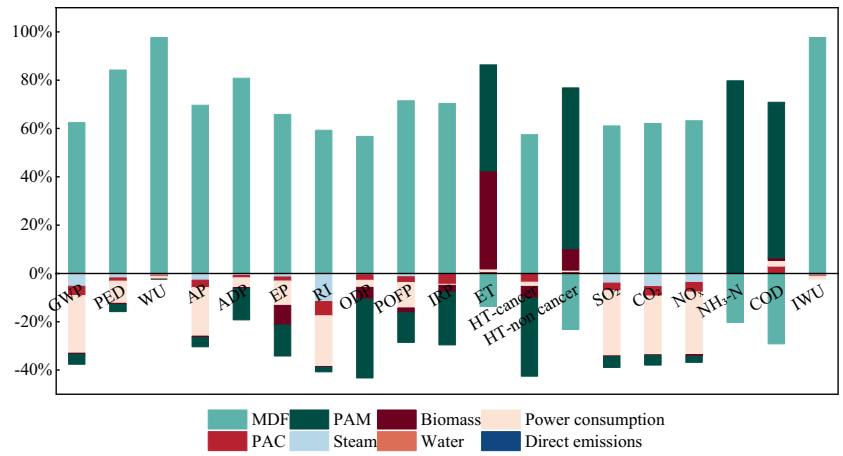
Fig. 2 Contribution analysis of life-cycle impact assessment

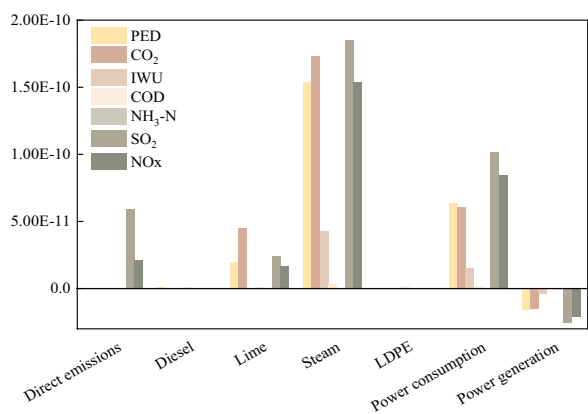


contribution to PED, IWU, and NO_x , resulting in changes of 5.31×10^{-12} , 1.69×10^{-12} , and 4.64×10^{-12} , respectively. For PMS-to-heat, a 5% variation of steam causes

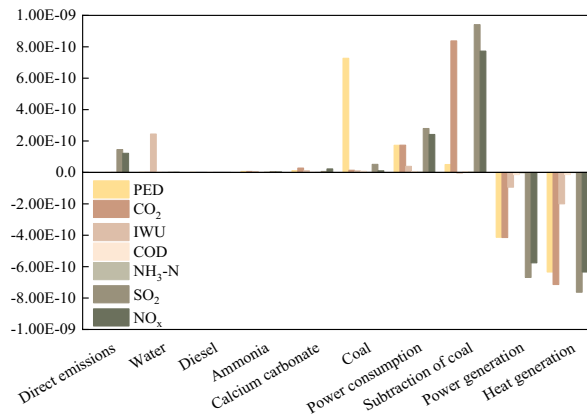
a marked variation in the ECER indicator. Coal has a significant impact on the change of SO_2 , with a variation value of -3.51×10^{-9} , which also causes a change rate

Fig. 2 (continued)

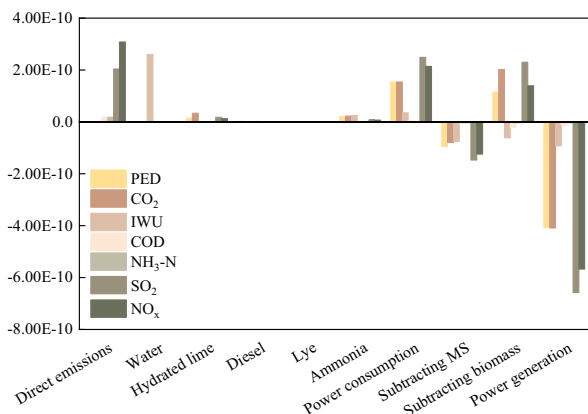




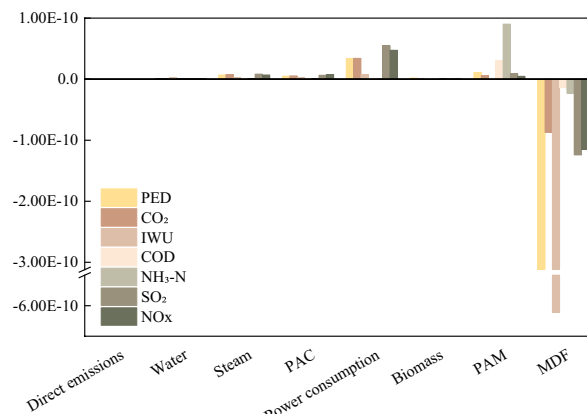
(a) Baseline



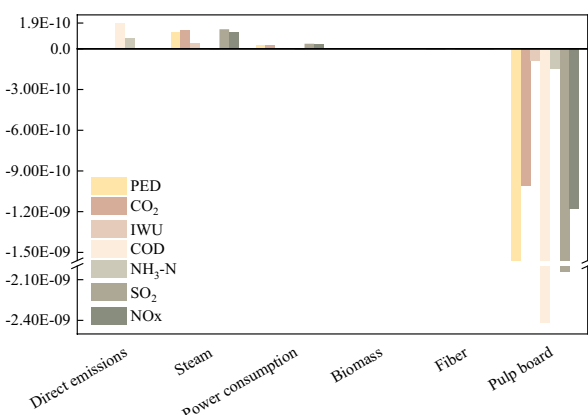
(b) PMS-to-heat



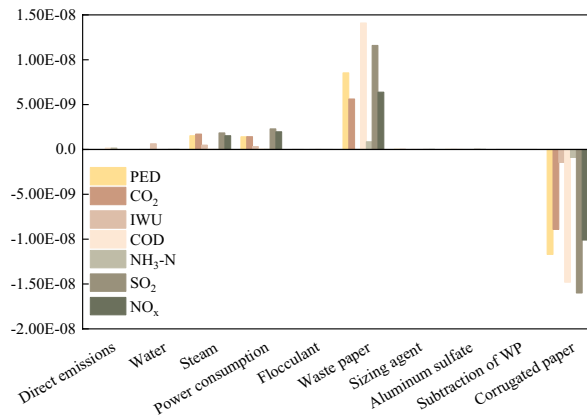
(c) PMS-to-electricity



(d) PMS-to-MDF



(e) PMS-to-pulp board



(f) PMS-to-corrugated paper

Fig. 3 Comprehensive normalized results within the six technologies

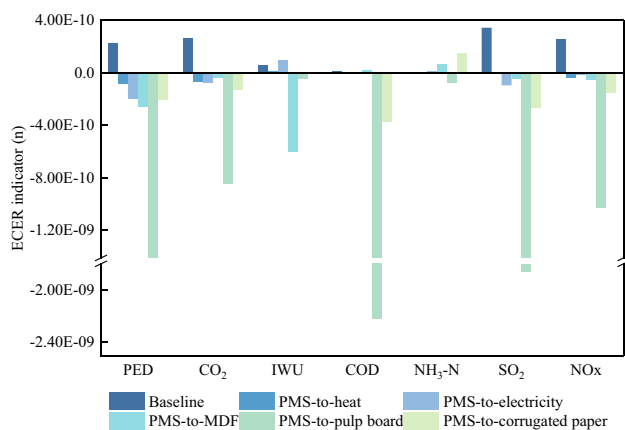


Fig. 4 Comprehensive normalized results between the six technologies

of -46.93% to PED. For PMS-to-electricity, changes for PED, CO_2 , and SO_2 caused by electricity generation are 10.47% , 27.38% , and 34.87% , respectively. For PMS-to-MDF, the product contributes observably to all environmental impact categories, and the changes are 6.15% , 12.87% , 5.12% , -3.49% , 1.71% , 13.77% , and 11.95% for PED, CO_2 , IWU, COD, $\text{NH}_3\text{-N}$, SO_2 , and NO_x , respectively. For PMS-to-pulp board, changes caused by product are 5.53% , 5.94% , 9.79% , 5.44% , 10.50% , 5.50% , and 5.76% for PED, CO_2 , IWU, COD, $\text{NH}_3\text{-N}$, SO_2 , and NO_x , respectively. The change rates of other raw materials and energy consumption are under 1% . For PMS-to-corrugated paper, the change rates of the steam used for drying products and the power required for the overall process to PED are -38.11% and -35.31% , respectively.

Uncertainty analysis

The detailed outcomes of the standard deviation of each input and the basic uncertainty are shown in the Supplemental Information; the Monte Carlo method is applied to diagnose the uncertainty of six technologies in this section. The simulation was performed using Oracle Crystal Ball software, with the values of the uncertain variables randomly sampled over a 95% confidence interval for 1000 iterations, which can visualize and quantify data (Bergamo et al. 2020). The CV of each inventory life cycle input is obtained by the combination of Pedigree Vector, Pedigree Matrix, and Basic Uncertainty Matrix to apply this simulation. The results show that the IWU in PMS-to-heat and $\text{HN}_3\text{-N}$ in PMS-to-electricity are greater than 15% , indicating that water consumption and emissions can have an important effect on the LCA results. In addition, the CV value of the COD index in PMS-to-MDF is 17.64% , indicating that the value is unstable and can be reduced by controlling the consumption of chemical agents.

Scenario analysis

GHG emissions in treating PMS vary from technologies. The GHG emissions for processing 1 t of dry PMS by using technologies, i.e., baseline, PMS-to-electricity, MDF, pulp board, and corrugated paper, are $3.27 \times 10^3\text{ kg CO}_2\text{ eq}$, $-8.98 \times 10^2\text{ kg CO}_2\text{ eq}$, $-3.51 \times 10^2\text{ kg CO}_2\text{ eq}$, $-8.73 \times 10^3\text{ kg CO}_2\text{ eq}$, and $-1.29 \times 10^3\text{ kg CO}_2\text{ eq}$, respectively. Based on the scenario assumptions in the “Data source and life cycle inventory”, the GHG emissions of four scenarios in each province were assessed. As shown in Fig. 5 and Appendix A, the GHG emissions for processing 1 t of dry PMS in scenarios 1, 2, 3, and 4 are $2.02 \times 10^3\text{ kg CO}_2\text{ eq}$, $2.7 \times 10^2\text{ kg CO}_2\text{ eq}$, $-1.75 \times 10^3\text{ kg CO}_2\text{ eq}$, and $-2.78 \times 10^3\text{ kg CO}_2\text{ eq}$, respectively. Scenario 1 represents the current situation of national PMS treatment, with the highest GHG emission of the four scenarios. In contrast, scenarios 2, 3, and 4 show an emission reduction potential, and the emission reductions increase in order. Based on the highest PMS paperboard technologies’ application rate, scenario 4 reduces GHG emissions ($4.80 \times 10^3\text{ kg CO}_2\text{ eq}$) compared to scenario 1. This is because the product of PMS paperboard technologies can lead to more environmental benefits than traditional landfill treatment. Therefore, adopting more PMS paperboard technologies and reducing the proportion of landfill is the key to GHG emission reduction, which requires strong support and promotion from the government and policies. If the nation carries out technology portfolio optimization to adopt the scenario 4 option for PMS treatment, then the national GHG emission reduction will reach $-9.08 \times 10^{10}\text{ kg CO}_2\text{ eq}$, which will have a significant emission reduction effect.

Economic analysis results

As shown in Fig. 6, LCC results for baseline, PMS-to-heat, electricity, MDF, pulp board, and corrugated paper are $\$ -35.63$, $\$ -113.02$, $\$ -121.27$, $\$ -183.65$, $\$ -257.36$, and $\$ -200.16$, respectively. For treating 1 tonne of dry PMS, the PMS-to-pulp board shows the highest economic benefits while the baseline has the lowest. This is because the PMS-to-pulp board has the highest revenue and the lowest electricity consumption, and landfill displays the lowest revenue.

Co-incineration is beneficial for heat and electricity generation but it can be costly due to the implantation of PMS drying and incineration facilities (Gievers et al. 2022), which is consistent with our findings. PMS-to-heat has the highest electricity consumption, leading to the most significant electricity consumption cost ($\$103.11$). Initial investment, raw materials, and revenue are the major contributors to economic costs. In particular, different from other technologies, PMS-to-electricity co-processing relies

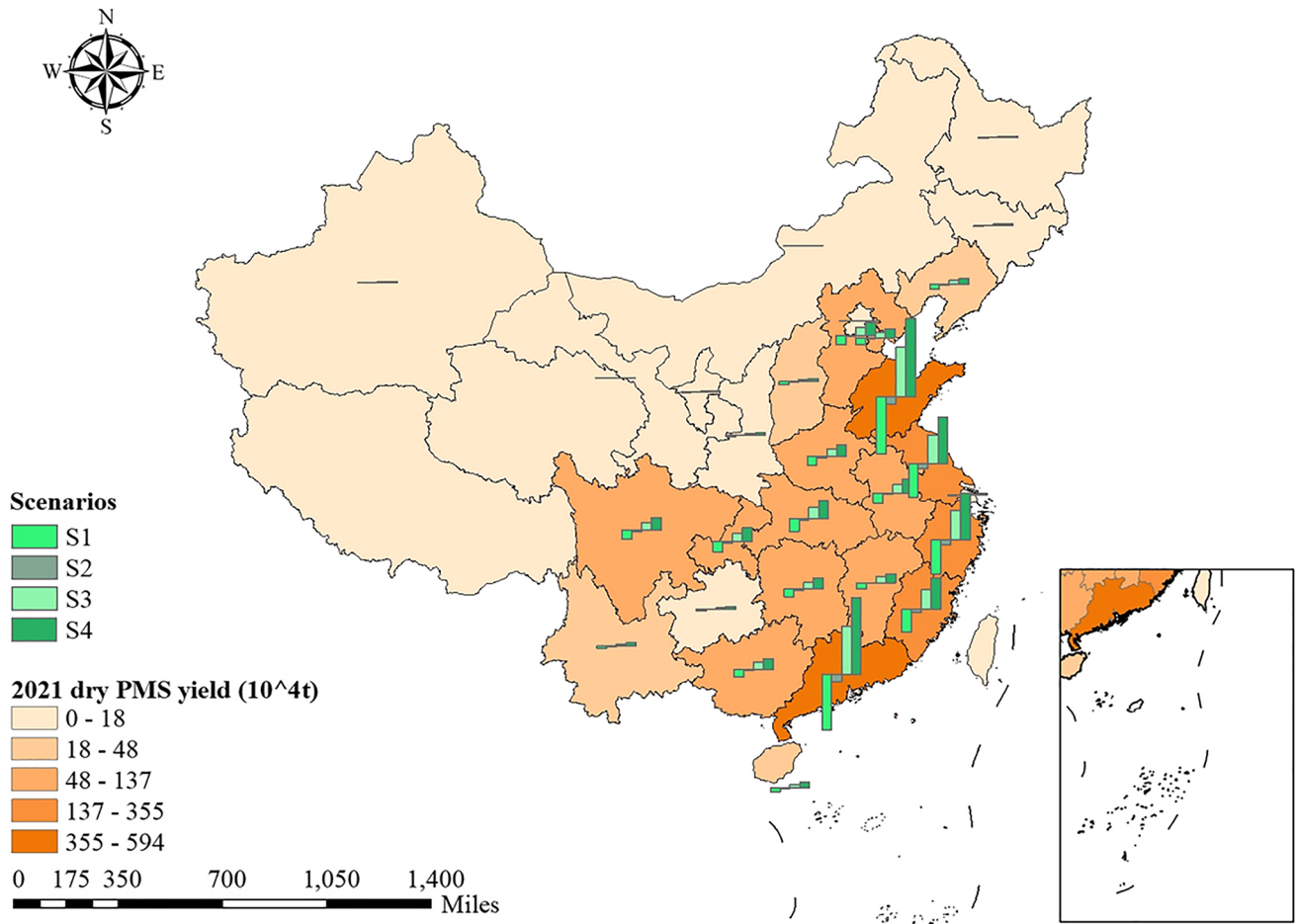
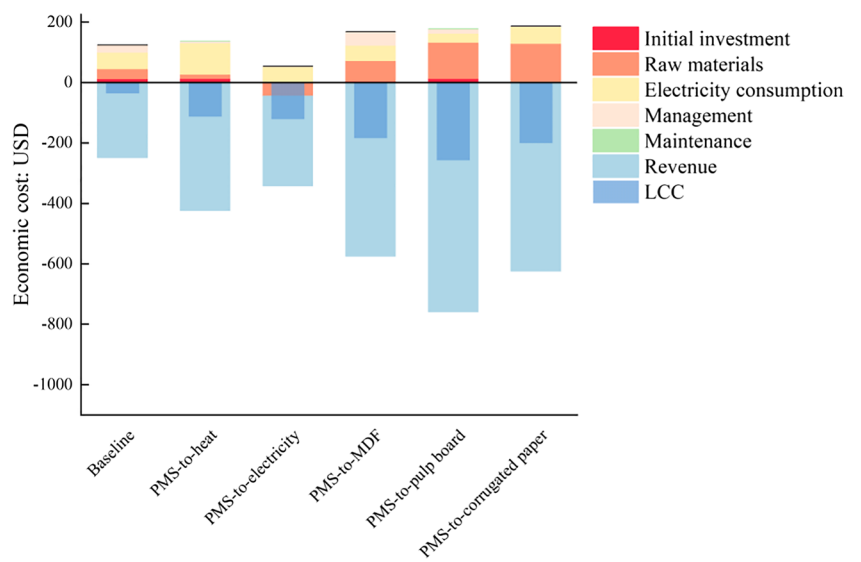


Fig. 5 National PMS production distribution and GHG emission reduction distribution

Fig. 6 Economic costs and LCC results for six technologies



on municipal sludge and biomass incineration for power generation. Therefore, the system boundaries between PMS, MS incineration for power generation, and biomass incineration for power generation need to be distinguished. The energy consumption, material consumption, and pollutant emissions of MS and biomass incineration are not included in the system boundary of PMS-to-electricity, so the raw materials in this list exhibit negative values in the economy with values of \$ - 45.33. For PMS-to-MDF, the management cost and raw materials are \$44.01 and \$68.17, respectively. The former is higher than the management costs of the other technologies. For the PMS-to-pulp board, initial investment (\$13.683) and maintenance cost (\$0.168) are higher than those of other technologies, but the highest revenue (\$759.254) and the lowest electricity consumption (\$29.241) contribute to the highest economic benefit. Revenue and electricity consumption are important factors in economic cost. For PMS-to-corrugated paper, which has the lowest initial investment (\$0.916), management cost (\$1.612), and maintenance cost (\$0.013), but the highest raw materials cost (\$128.938) shows a significant contribution to LCC results.

Discussion

PMS treatment and resource utilization

The government encourages paper mills to reduce emissions and concentrations of waste gas and wastewater through the introduction of advanced flue gas and wastewater purification equipment, ensuring compliance with national standards in China. In the “Outline of the plan for the construction of a conservation-oriented society,” the government also encourages comprehensive waste utilization and resource recycling in the paper industry. PMS reutilization is the desirable environmental option for treating PMS since it can produce potential value-added products. Meanwhile, the environmental issues caused by the resource utilization of PMS have become the focus of the paper industry towards a circular economy.

Research limitations

The data for each technology are from different companies and may deviate from the industry, and there are limitations and uncertainties in this paper. We have made some assumptions to unify the functional unit and PMS components. To avoid some undesirable distractions, we give some prerequisites (Table S4).

Prospects for future research

Among the baseline and two energy utilization technologies, electricity consumption is the main contributor to environmental impact, and the electricity consumed is the most commonly used coal-fired power. However, in an attempt to reduce the energy-related CO₂ emissions as well as our reliance on the diminishing fossil-fuel reserves, various renewables are being considered potentially more sustainable sources of electricity, including photovoltaic, wind, and biomass. In this study, if coal-fired power generation is replaced by photovoltaic, wind, and biomass power generation, CO₂ emissions from electricity consumption can be reduced at the source, and the total environmental impact of the treatment process can be made smaller. Wang et al. (2014) found that in 2020, solar photovoltaic power generation could save 17.4 Mtce fossil energy and 46.5 Tg CO₂, compared with 600 MWe coal-fired supercritical units. For 1 kWh, wind power only consumes 4% of the total amount of CO₂ emissions and environmental costs related to coal power (Li et al. 2020a). The co-incineration of biomass-based substitutes is also regarded as a highly cost-effective and short-term method of reducing CO₂ emissions in the electricity sector (Knapp et al. 2019). According to our previous studies, the substitution of biomass for coal as an auxiliary fuel in sludge incineration has a better environmental impact, reducing ECER value by 3.08×10^{-10} , and increasing economic benefits by 33.4% (Liu et al. 2023c). In addition, Cui et al. (2021) have detailed how to structure a high-ambition coal plant phaseout in China to facilitate a rapid energy transition. In general, the use of renewable energy power generation to replace traditional coal power generation has enormous emission reduction potential and development value.

In the future, the work could be enhanced by performing a more complete and robust analysis by combining technical, economic, and social factors. It is also worthy of discussing more energy substitution scenarios in order to safeguard higher environmental and economic benefits. Meanwhile, further research should be conducted to study the reliability, durability, and environmental friendliness of the products obtained from the resource utilization of PMS. The preparation of fiberboard, activated carbon adsorbent, and other high-value utilization of PMS still needs further research.

Conclusions

The baseline, incineration technologies (PMS-to-heat, electricity), and paperboard technologies (PMS-to-MDF, pulp board, and corrugated paper) were evaluated and compared from environmental and economic perspectives. For PMS

incineration technologies, PMS replaces fossil fuels to provide heat and makes PMS-to-heat/electricity lead to environmental benefits. PMS-to-electricity outperforms PMS-to-heat in the environment because the former consumes biomass instead of coal as an auxiliary fuel compared to the latter. The three paperboard technologies perform better environmental benefits compared to the incineration technologies. From the normalization results, ECER indicators in descending order are baseline > PMS-to-heat > PMS-to-electricity > PMS-to-corrugated paper > PMS-to-MDF > PMS-to-pulp board. Therefore, the environmental impact of PMS-to-pulp board is the smallest while landfill is the highest. The LCC results show that the PMS-to-pulp board exhibits the highest economic benefits due to the greatest product revenue, and PMS-to-electricity has the least economic benefits apart from landfills. In conclusion, the high-value utilization of PMS to produce paperboard is a sustainable development model for reducing environmental impacts and promoting a circular economy and should be recommended.

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Author contribution Yanfei Lin: conceptualization, methodology, data curation, writing—original draft. Guoxia Wei: writing—review and editing. Hanqiao Liu: conceptualization, methodology, writing—review and editing. Kai Li: methodology and editing. Yuwen Zhu: conceptualization, writing—review and editing. Qianlong Han: conceptualization, methodology, writing—review and editing. Yunzhen Yang: writing—review and editing. Yi Lian: writing—review and editing.

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Data availability The data that supports the findings of this study are available in the Supplementary Information.

Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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