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Article

Investigating Waste-to-Value Conversion Efficiency Within Circular Economy Frameworks for Sustainable Paper Products Industries

Nguyen Phuong Minh

St. Anthony's High School, 275 Wolf Hill Road, South Huntington, NY 11747, USA, npminh.sa@gmail.com

Abstract: The increasing amounts of industrial and post-consumer paper waste have increased the importance for effective conversion technologies that aid resource recovery, sustainability, and circular economy implementation to the paper products industry. Existing research mainly focusses on specific paper waste valorization applications, while integrated evaluation of conversion efficiency, environmental sustainability, circularity performance, and economic feasibility remains limited. Research investigates Waste-to-Value Conversion Efficiency (WTVC-E) in sustainable paper product industries by assessing material recovery, environmental impact reduction, circular economy performance, and economic sustainability. The research variables involve WTVC-E, Fiber Recovery Yield (FRY), Processing Loss Rate (PLR), Water Reuse Efficiency (WRE), Energy Consumption Efficiency (ECE), Environmental Impact Reduction Index (EIRI), Economic Return Efficiency (ERE) and Circular Economy Performance Index (CEPI). Data were gathered from fifteen paper manufacturing plants, recycling facilities, and waste collection centers over a continuous twelve-month period through production records, waste recovery logs, environmental monitoring reports, and financial performance records, yielding N = 180 operational observations. It was conducted using Material Flow Analysis (MFA), Life Cycle Assessment (LCA), Circularity Performance Assessment and Economic Sustainability Assessment. Statistical analysis using SPSS 28 was performed using Descriptive Statistics, Shapiro-Wilk Test, Multiple Regression, Pearson Correlation, Chi-Square Test and Multicollinearity analysis. Results indicated 66.7% material recovery efficiency, 6.8 tons/day FRY, and 21.7% ERE. Multiple regression analysis identified CEPI ($\beta = 0.338$, $p < 0.001$) as strongest predictor of WTVC-E. It concludes that waste-to-value conversion models significantly strengthen circular economy implementation by improving industrial sustainability, economic resilience, resource conservation, and long-term environmental management efficiency in paper product manufacturing sectors.

Keywords: Waste-to-Value Conversion, Circular Economy, Paper Waste Recycling, Resource Recovery Efficiency, Sustainable Paper Industries, Economic Recovery Analysis

1. Introduction

The rapid growth of industrialization, development, and expansion of population has significantly increased the generation of waste across the world, creating serious environmental, economic, and social concerns. Global municipal solid waste generation has increased steadily over the past decades and is projected to exceed 3.8 billion tonnes annually in the coming years [1]. The Constant generation of waste puts a lot of strain on landfills and causes environmental pollution, emission of greenhouse gases, and the faster depletion of natural resources [2]. As a consequence of this scenario, sustainable resource management becomes all the more essential as it seeks to minimize waste generation and optimize resource usage. In response of these issues, sustainable development has become an important paradigm which allows for economic growth and environmental preservation while improving societal welfare [3]. Sustainability-driven production models motivate industries to be more efficient, consume fewer

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resources, and employ environmental-friendly practices in waste management. Among many methods of sustainability, the circular economy is emerging as a revolutionary concept that promises to lead towards sustainable resource use and environmental sustainability [4].

The circular economy paradigm is an evolution from the linear economics system, which involves high resource consumption and waste creation. The idea behind the circular economy is focused on reducing waste and maximizing reuse of resources to retain the value of materials in the economic environment for as long as possible [5]. With circular economy, closed loop material flow processes will minimize adverse effects on the environment and save natural resources and promote sustainable industrial systems [6]. Therefore, most manufacturers have been adopting the idea of the circular economy in their business models to improve their resource productivity and reduce waste disposal. In resource-intensive industries, the paper products industry is crucial for economic development and day-to-day activities by humans [7]. Paper and paper products have extensive uses in packaging, educational institutions, printing, publishing, personal hygiene products, and commercial operations. The increase in the use of e-commerce, consumers, and packaging demands has contributed further to the global demand for paper products [8]. Although being economically significant, the paper industry is known for its high consumption of raw materials, water, and energy during the manufacturing process. The removal and processing of fiber materials also lead to deforestation, loss of biodiversity, and environmental degradation [9].

Apart from intensive consumption of resources, the paper industry also produces substantial amounts of wastes at the stages of production, processing, and disposal. The wastes produced by the paper industry are paper scrap, pulp waste, deinking sludge, sewage sludge, fiber rejects, and waste paper from homes and commercial organizations [10]. Conventionally, there has been a major part of such wastes which has been disposed of using either landfilling or incineration techniques, thereby causing environmental impact and financial loss. Nevertheless, because of the ability of paper-based material waste to be recycled and decomposed, there is significant capacity for recovering resources from such waste [11].

The increasing focus on sustainable management of resources has led to greater importance being placed on waste valorization as a possible means of turning waste products into economically beneficial assets. Waste valorization, alternatively known as the process of converting waste to value, entails the recovery and processing of waste to produce value-added products like raw materials, energy products, bio-materials, etc [12]. Using advanced technology and improved recycling techniques, paper waste are turned into recycled fibers, biofuels, biochar, bio composites, building materials, and various other commercial products [13].

The conversion of waste to value not only helps in reducing the volume of waste for disposal but also aids in resource conservation and saving energy as well as minimizing greenhouse gas emissions. Moreover, the extraction of useful resources from waste streams may lead to further financial gains and enhance the environmental efficiency of the industrial process [14]. Thus, waste valorization has turned into an integral part of the process of circular economy adoption in industrial areas, especially in those industries where a large amount of waste is produced [15].

However, despite the existence of many waste recovery techniques that apply to paper wastes, differences in terms of conversion rate, resource recovery rate, environmental gain, and economic feasibility still pose serious problems [16]. Additionally, understanding regarding the role that circular economy plays in enhancing efficiency in the waste recovery system aid decision-makers who aim at improving their sustainability performance and securing competitiveness [17].

Paper sludge conversion into high-value cellulose acetate films, useful in environmentally friendly packaging of foods, has been carried out by [18]. In the process, paper sludge-derived cellulose fibers have been purified, acetylated, and formed into cellulose acetate films, which have been further analyzed for their barrier properties, followed by barrier property analyses. Results showed reduced hydrophilicity, while the films demonstrated excellent water barrier performance at 50% and 90% relative humidity (RH). However, it does not assess large-scale production feasibility, long-term durability, or economic viability. Research [19] developed sustainable and recyclable Three-dimensional (3D)-printing inks from waste paper, cellulose-rich paper waste were converted into direct ink writing

(DIW) inks, producing 3D constructs with good printability, thermal stability up to 200°C, and compressive strength of 6–8 MPa; however, the material is mainly limited to paper-based feedstocks and exhibits lower mechanical performance than advanced polymer-based 3D-printing materials.

1.1 Problem Statement: The sustainable paper products industry faces challenges in efficiently converting increasing volumes of paper waste into valuable resources, limiting resource recovery, environmental sustainability, and circular economy implementation. To overcome these problems, an investigation of the Waste-to-Value Conversion Efficiency (WTVC-E) processes within circular economy models is performed here by evaluating resource recovery, environmental sustainability, and economic performance in sustainable paper product industries.

1.2 Key contributions of the research

- An analysis of WTVC-E of recyclable paper waste within circular economy models by evaluating resource recovery, environmental sustainability, and economic performance is done in this research.
- Data was obtained from fifteen paper factories, recycling plants, and garbage disposal facilities for a period of one year without interruption, resulting in a total of 180 operations recorded through manufacturing documents, waste recovery documents, environmental monitoring, and financial performance reports.
- The research utilized Material Flow Analysis (MFA), Life Cycle Assessment (LCA), Circularity Performance Assessment, and Economic Sustainability Assessment.
- Analysis of results with SPSS 28 included the following analyses: descriptive statistics, Shapiro-Wilk Test, Pearson correlation, multiple regression, multicollinearity test, and Chi-Square test.

Research Organization: Section 1 presents waste to value and circular economy principles in the paper industry. Section 2 reviews recent literature and recognizes the research gap. Section 3 and 4 describes the research design and analytical framework. Section 5 offers the results and discussion and Section 6 concludes with restrictions and future research.

2. Related Works

Recent research collectively emphasized waste-to-value approaches in paper industries, highlighting efficiency, and methodological diversity with outcomes and limitations. Evaluation of paper waste sludge (PWS) as a sustainable alternative to commercial adsorbents for stabilized leachate treatment; batch adsorption experiments were conducted by [20] under optimized conditions, and results achieved 62% Chemical Oxygen Demand (COD) removal, providing the best fit, while being insufficient for stringent wastewater treatment requirements without further process enhancement. Research [21] evaluated the agricultural and brewing by-products as sustainable additives for recyclable food-packaging paper, grain residues and brewer's yeast (10 wt%) were incorporated into Northern bleached softwood kraft (NBSK) and Chemi thermomechanical pulps (CTMP) using a standard sheet-forming process; results showed improved hydrophobicity, flexibility, and CTMP surface roughness, while higher filler concentrations reduced tensile strength, tear resistance, and bending stiffness; however, it reduced mechanical performance, particularly at higher filler loadings. The energy recovery potential of waste paper (WP) and deinking sludge (DIS) for sustainable power generation in the paper industry was evaluated by [22]. A numerical air-gasification model combined with an internal combustion engine was applied at an optimum temperature; results demonstrated electrical and thermal energy generation potentials of 32,950–35,700 GWh and 52,190–56,100 GWh, respectively; however, the findings are based on simulation and require large-scale experimental validation and economic feasibility assessment for industrial implementation. Research [23] measured the suitability of Deinking Paper Sludge (DPS) as a sustainable growing substrate, where comprehensive chemical, elemental, spectroscopic Diffuse Reflectance Infrared Fourier Transform (DRIFT), Fourier-transform infrared (FTIR), and thermogravimetric analyses were conducted; results showed high organic matter and carbon content, adequate mineral nutrients, and trace metal concentrations below regulatory limits, with no detectable toxic heavy metals, but restricted to low nitrogen availability to optimize plant growth and soil

fertility. Development of a sustainable and lightweight electromagnetic interference (EMI) shielding material was done by [24] through recycling waste ethylene propylene diene monomer (EPDM) rubber from end-of-life vehicle bumpers; the material was fabricated through internal melt mixing of waste EPDM, and carbon nanotube (CNT) nanofillers, achieving an electrical conductivity. Results provided that EMI shielding effectiveness of 30.4 dB and improvements of 46% in yield strain but were limited by the lack of large-scale industrial validation and long-term performance assessment.

Identification of key factors influencing recycled raw materials trade as a major indicator of Circular Economy (CE) development was performed by [25] using panel data analysis, regression matrix construction, and dynamic regression modelling. Relationships between recyclable trade and CE indicators were examined, which revealed a positive correlation between trade in recyclables and private investments in circular economy sectors, showing no significant autocorrelation; however, it mainly focused on trade-related indicators and did not fully capture all dimensions of circular economy transition. Investigation of the effects of aging and recycling on the optical properties of paperboard for sustainable packaging applications was performed by [26] using deinking flotation, optical measurements, and regression analysis, which revealed significant changes in chromatic coefficients, and reduced fluorescent effects after recycling, indicating structural modifications; however, it did not evaluate the mechanical performance or long-term industrial applicability of recycled paperboard. Valorization of secondary Paper Mill Sludge (PMS) into sustainable products was investigated by [27] using dewatering, grinding, and blending processes to manufacture eco-friendly composites, which produced bricks with a compressive strength of 5.29 ± 0.11 N/mm², and water absorption of $3.84 \pm 0.13\%$, but it did not assess large-scale production feasibility, economic viability, or long-term durability under field conditions.

Valorization of PMS as a low-cost biosorbent for wastewater treatment was investigated by [28] using physico-chemical characterization, adsorption experiments, isotherm modeling, and kinetic analysis for Methylene Blue (MB) dye removal, which demonstrated a maximum adsorption capacity of 43.5 mg g^{-1}, providing the best fit, while adsorption was found to be spontaneous but did not evaluate performance under real industrial wastewater treatment conditions. High-value utilization of Digital Printing Waste paper Fiber (DPWF) was investigated by [29] through its incorporation into melt-blended thermoplastic resin composites, which revealed that the optimal mechanical properties were achieved at 35% DPWF content and improved with 3% coupling agent resulting in enhanced interfacial bonding and thermal properties but did not evaluate the long-term durability and large-scale industrial feasibility. The influence of repeated paper recycling loops on fiber yield and paper strength was investigated by [30] using papermaking processes, which revealed that strength of paper remained relatively stable and average fiber yields were below 70% per recycle; however, it does not fully represent losses in large-scale industrial recycling systems.

2.1 Research gap

Existing research [20-30] predominantly examined specific paper waste valorization applications such as particleboards, wastewater treatment, packaging materials, energy recovery, and soil amendments. However, integrated assessment of WTVC-E within circular economy frameworks, considering recovery effectiveness, economic feasibility, and sustainability performance in paper product industries, remains insufficiently explored. However, this research addresses these challenges by considering MFA, LCA, circularity index, and efficiency modeling approaches in assessing material, environmental, resource, and economic performance of paper industry circular economy systems.

3. Research variables

The chosen research variables that are listed in Table 1 have been used to evaluate the efficiency of converting wastes to value using circular economy-based paper recycling systems. This evaluates material recovery, loss during the process, energy and water usage, reduction of environmental impacts, economic gains, and circular resources management to assess the effectiveness of sustainable approaches to making paper products.

Table 1. Tabulation providing the description of the research variables

Variable	Description
Dependent Variable	
Waste-to-Value Conversion Efficiency (WTVC-E)	It reflects the efficiency of the process of converting waste paper into reusable resources by achieving maximum recovery, reducing losses, and improving environmental and economic efficiency in a circular economy.
Independent Variables	
Fiber Recovery Yield (FRY)	It is the measurement of the number of reusable fibers successfully recovered from the waste paper through recycling activities, which shows the efficiency of the recycling processes and resource recovery performance.
Processing Loss Rate (PLR)	It is an indicator that shows the loss of materials during sorting, pulping, de-inking, and recycling processes, which is an indication of the inefficiency involved in the whole process.
Water Reuse Efficiency (WRE)	It evaluates the ability of recycling operations to recover, treat, and reuse process water, reducing freshwater consumption and supporting sustainable industrial resource management.
Energy Consumption Efficiency (ECE)	It measures the effectiveness of utilizing energy resources during waste processing and recycling operations while minimizing energy requirements per unit of recovered product output.
Environmental Impact Reduction Index (EIRI)	It quantifies the extent to which waste-to-value practices reduce emissions, waste disposal, resource depletion, and ecological burdens compared with conventional production systems.
Economic Return Efficiency (ERE)	It assesses the financial benefits generated through resource recovery activities by comparing cost savings, operational expenditures, and revenue gains from recycled material utilization.
Circular Economy Performance Index (CEPI)	It is a complex sustainable development indicator that measures the achievement of the circular economy in paper recycling activities. It includes significant parameters such as recycling efficiency, resource recovery rate, waste diversion, and material recirculation. High scores on the CEPI show high circularity and efficient reuse of recovered materials and index is employed to examine its role in improving WTVC-E.

These variables were derived based on the data on operational, environmental, and economical performances of paper recycling processes. The values for FRY and PLR were derived from material recovery and processing losses data, whereas the values for WRE and ECE were computed based on water and energy usage. The EIRI was measured using environmental measures pertaining to emission reduction, minimization of waste, and resource conservation results. ERE was determined based on economic data such as cost savings, operation costs, and profits gained through recycling operations. CEPI was calculated using performance indicators within the context of circular economy, such as recycling efficiency, resource recovery efficiency, waste diversion, and material recirculation efficiency.

4. Materials and Methods

An Investigation of the use of WTVC-E for recyclable paper waste under the context of circular economy models, looking into issues such as resource recovery, environmental sustainability, and efficiency in the paper industry. Research adopted a quantitative approach to analyze the WTVC-E based on industrial performance and sustainability indicators. The data used in the analysis was collected from paper recycling and manufacturing plants and arranged systematically for further analysis. Research design comprised data collection, measurement of the variables, MFA analysis of material recovery, LCA analysis for the environmental performance, circular economy performance analysis, economic sustainability analysis, and SPSS statistical analysis to investigate the effect of the research variables. Figure 1 provides the Methodology flow.

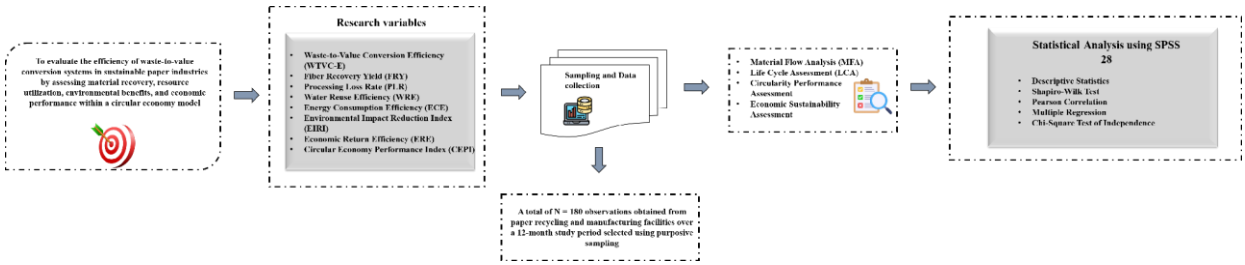


Figure 1. Visual representation showing the methodology flow

4.1 Data Collection

A quantitative research method was used to measure the effectiveness of waste-to-value transformation in circular economy-enabled paper recycling systems. Data were gathered from fifteen paper manufacturing plants, recycling facilities, and waste collection centers that were involved in the process of recovering paper waste and producing through circular processes. The operational records containing information about twelve-month period were gathered from the organizations taking part in this research. The monthly observations regarding the measures related to material recovery, efficiency, environment, and economy were recorded through their production, waste recovery, environmental, and performance records. It involved 180 observation periods (15 facilities × 12 months), and data gathered were checked to confirm completeness, consistency, and operational reliability. These records included quantified data regarding fiber recovery, loss of material during processing, water re-use, energy efficiency, decreased environmental impact, financial gain, and circular economy performance.

4.2 Sampling Technique

Purposive sampling was used to identify organizations that is useful in helping attain the research objectives. Organizations that were using activities related to circular production, including resource recovery and recycling of paper wastes, were deliberately chosen for the research.

4.3 Selection criteria

Criteria for selection were set up such that only those facilities that have the capability of value conversion of their wastes, have the concept of circular economy as well as experience, would be considered for the research. This helped achieve efficiency and consistency in data regarding efficiency and sustainability performance.

4.3.1 Inclusion Criteria

The research included paper manufacturing plants, recycling facilities, and waste collection centers that met the following conditions:

✓ Facilities actively involved in paper waste recycling activities.

✓ Facilities applying a circular economy approach or resource recovery process.

✓ Facilities with well-recorded operational processes related to production, waste recovery, environment, and economics.

✓ Facilities ready to share industry information for research purposes.

4.3.2 Exclusion Criteria

The following facilities were excluded from the research:

✓ Facilities with inadequate documentation regarding operations or sustainability.

- ✓ Facilities without comprehensive information on materials recovery, water use, energy consumption, and financial performance.
- ✓ Facilities without adequate documentation for the research variables.
- ✓ Facilities engaged only in waste disposal but not in any form of resource recovery or recycling.

Facilities which did not want to participate or failed to provide consistent data.

4.4 Analytical Framework

After data collection, sampling, and facility selection, the collected data on operational data, environmental data, and economic data were arranged for analysis purposes. Analysis was based on the model that employed MFA, LCA, Circularity Performance Assessment, and Economic Sustainability Assessment. Material Recovery Performance, Environmental Performance, Circular Economy Performance, and Economic Performance were analyzed.

4.4.1 Material Flow Analysis (MFA)

MFA was utilized in the evaluation of movement and transformation of the waste paper material within the recycling process. The analysis considered the operations of great importance to the recycling process, like the collection of waste materials, sorting of waste materials, pulping of waste materials, processing of the waste materials, and finally production of end products. The aim was to assess the flow of resources within the recycling industry and thus help in identifying any inefficiency within the process of resource management. System performance was analyzed based on Total Waste Input, which is an index of the volume of paper waste input into the recycling/recovery system. Additionally, another index known as Material Recovery Efficiency was also used in analyzing the efficacy of downstream recovery processes. The generation of losses during the processing stage was also studied to comprehend inefficiencies within the system level. In this context, fiber recovery efficiencies and processing losses were assessed through FRY and PLR, indicating fiber extraction efficiency and losses incurred during recycling processes, respectively.

4.4.2 Life Cycle Assessment (LCA)

LCA assesses the environmental performance of the waste-to-value system. The evaluation looked into significant phases of operation that include waste transfer, recycling process, energy consumption, and water consumption in the paper-making industry. Environmental sustainability was measured through WRE and ECE, which measure the efficiency of resource consumption in the recycling process. Environmental performance was measured using the EIRI, which takes into account the reduction in carbon emission (CO_2), resource use, and pollution generated because of the use of circular recycling techniques. CO_2 Reduction is the reduction in the release of greenhouse gases because of recycling operations relative to paper manufacturing processes without recycling operations. This provided a comprehensive evaluation of the environmental effect of waste-to-value processes.

4.4.3 Circularity Performance Assessment

Circularity Performance Assessment was conducted to assess the effectiveness of integration of circular economy in the paper recycling process. The assessment considered the level of resource circulation, re-use intensity, and waste reduction resulting from industrial recycling processes. Performance of the circular system was assessed based on three important circularity parameters, namely Recycling Rate, Resource Recovery Rate, and Waste Diversion Rate. Recycling Rate refers to the amount of collected paper waste which is effectively recycled and transformed into recyclables. Resource Recovery Rate is the percentage of useful resources retrieved from the waste stream to be used again. The Waste Diversion Rate is the amount of waste diverted from landfills and sent for recycling or recovering purposes. These parameters basically denote the level of material reintegration in the production process, the extent of resource recovery from the waste flow, and the reduction in the number of landfills generated. Circular performance as acaptured in terms of CEPI, which is based on the recycling, reuse, and reduction processes.

4.4.4 Economic Sustainability Assessment

Circular performance is evaluated against the CEPI, an indicator of the overall effectiveness of recycling, resources circulation, and waste reduction methods in the process. Economic sustainability is determined by evaluating the economic feasibility and efficiency of the waste-to-value process system. To depend on the economic costs, income, and benefits gained from paper recycling practices. Cost savings are defined as the reduction of expenses incurred by the process through reduced use of virgin materials and waste elimination processes. Revenue from Recycling refers to the monetary gains made from the recycling of paper fibers. Net benefit refers to the overall financial benefit gained from subtracting total costs from the revenue made from recycling. Economic Sustainability was determined using the ERE, which compares the financial gains from recycling activities against the total cost incurred in the process.

4.5 Statistical Analysis

Statistical Analysis was employed to measure relationships, significance, and effect predictability among variables associated with the transformation from waste into value in sustainability performance through the circular economy approach. It employed SPSS version 28 using the following tests, with an overall statistical significance level set at $p < 0.05$.

✓ **Descriptive Statistics** was applied to describe the characteristics of data in relation to measures of central tendency and dispersal to give clear view of data characteristics across all variables under research.

$$s^2 = \frac{\sum_{i=1}^{n} (x_i - \underline{x})}{n-1} \quad (1)$$

Here in Equation (1), s^2represents variance, $x_i$denotes each observation, $\grave{x}$indicates the mean value, n and i refer to the total number of observations, and $\sum$represents summation.

✓ **Shapiro-Wilk test** was accomplished to determine whether the data fit into a normal distribution pattern, which make the data suitable for parametric tests within the research model. This is formulated using Equation (2),

$$W = \frac{\left(\sum_{i=1}^{n} a_i x_{(i)}\right)^2}{\sum_{i=1}^{n} (x_i - \underline{x})^2} \quad (2)$$

Here, W is Shapiro–Wilk test statistic, n is total number of observations with index i, a_i is coefficient, $x_{(i)}$ is ith ordered sample observation, x_i is original observation, $\underline{x}$ is Mean and $\sum$represents summation.

✓ **Pearson Correlation Analysis** was conducted to determine the presence and nature of relationships among the research variables to determine the relationship among the Waste-to-Value conversion within the research model. It is described as Equation (3)

$$r = \frac{n\left(\sum xy\right) - \left(\sum x\right)\left(\sum y\right)}{\sqrt{\left[n\sum x^2 - \left(\sum x\right)^2\right] - \left[n\sum y^2 - \left(\sum y\right)^2\right]}} \quad (3)$$

where r represents the Pearson correlation coefficient, $n$denotes the total number of observations included in the analysis. $\sum xy$ signifies the sum of the products of paired values of variables $x$and y, reflecting how both variables vary together. $\sum x$and $\sum y$indicate the total sums of individual values of variables $x$and y, respectively. $\sum x^2$and $\sum y^2$represent the sums of squared values for each variable, used to measure individual variability. The numerator $n(\sum xy) - (\sum x)(\sum y)$calculates the covariance, while the denominator standardizes this relationship by incorporating the variability of both variables

✓ **Multiple Regression Analysis** was applied in examining the combined effect as well as the individual effect of independent variables towards WTVC-E, which allows the identification of factors affecting performance. This is calculated using Equation (4),

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \varepsilon \quad (4)$$

Here, Y is dependent variable, β_0 is intercept, $\beta_1, \beta_2, \ldots$ are regression coefficients, $X_1, X_2, \ldots$ are independent variables, with ε as random error.

✓ **A Chi-Square Test** was applied to test presence of dependency among categorical variables, identifying any relationships that are present between research variables. It represented as Equation (5),

$$\chi^2 = \sum \frac{(O_i - E_i)^2}{E_i} \quad (5)$$

Here, O_i is Observed frequency, χ^2 is Chi-square test statistic, E_i is Expected frequency with index i.

✓ **Multicollinearity analysis** is performed to verify the independence of FRY, PLR, WRE, ECE, EIRI, ERE, and CEPI and ensure that these predictor variables do not exhibit excessive intercorrelation that affect the accuracy and reliability of the WTVC-E regression model

5. Result and discussion

An investigation of the efficiency of waste-to-value conversion of recyclable paper waste within circular economy models to enhance resource recovery, environmental sustainability, and economic performance in paper product industries was done in this research. The empirical analysis was carried out using SPSS Version 28, incorporating descriptive statistics, the Shapiro-Wilk normality test, Pearson correlation analysis, multiple regression analysis, and the Chi-Square test. In addition, system-level evaluations were performed using MFA, LCA, economic sustainability assessment, and circular economy performance evaluation to support a comprehensive and integrated analytical model for the research.

5.1 Descriptive Statistics

The descriptive analysis was performed to summarize the characteristics of data across all research variables. Mean refers to the average of each variable, Standard Error (SE) depicts dispersion in relation to the mean value, while minimum is the lowermost value observed and maximum is the highest value found within the set of data. This set of summary measures allows for a comprehensive description of data distribution as well as variation. Summary measures of central tendency and dispersion are shown in Table 2.

Table 2. Descriptive statistics summarizing central tendency and variability of variables

Variables	Mean	SE	Minimum	Maximum
WTVC-E	78.42	6.91	62.10	91.30
FRY	6.80	1.12	4.50	9.10
PLR	12.35	2.41	8.10	17.90
WRE	71.28	5.67	58.40	82.60
ECE	0.64	0.09	0.45	0.82
EIRI	74.91	7.02	59.80	89.40
ERE	21.70	4.15	12.80	30.50
CEPI	0.76	0.08	0.58	0.89

The statistical analysis shows that WTVC-E has a mean of 78.42% (SE = 6.91) with relatively high levels of waste-to-value conversion efficiency. The mean for CEPI was 0.76, while the average for EIRI was 74.91%. The level of PLR was relatively low at 12.35%.

5.2 Shapiro-Wilk Normality Test

The Shapiro-Wilk test was utilised to determine whether the data distribution was normally distributed, thus making it appropriate for use in the study. This test produced a statistic known as W, which determines how well the data approximates a normal distribution, together with probability value (p). This has been shown in Table 3.

Table 3. Shapiro–Wilk test assessing data normality across all variables

Variables	W Statistic	p-value
WTVC-E	0.972	0.081
FRY	0.965	0.064
PLR	0.958	0.052
WRE	0.971	0.077
ECE	0.963	0.058
EIRI	0.969	0.069
ERE	0.976	0.092
CEPI	0.981	0.104

The result was values of W statistic from 0.958 to 0.981 and p values from 0.052 to 0.104. Because all p values were higher than 0.05, normality was satisfied. The results show that the data were normally distributed. This is visually verified in Figure 2.

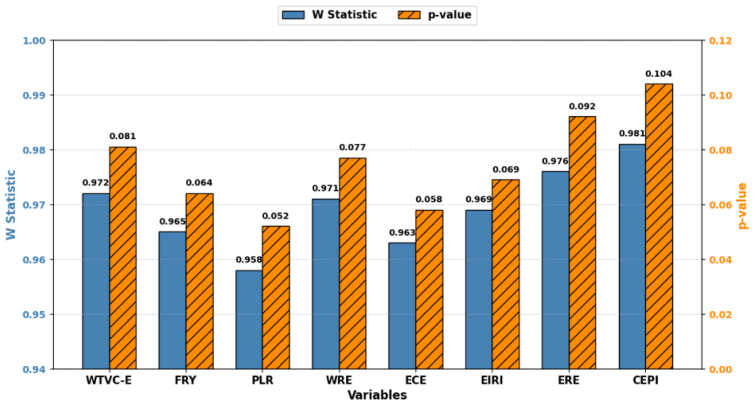


Figure 2. Graphical representation of Shapiro–Wilk analysis

5.3 Pearson Correlation Analysis

Pearson correlation analysis is used to calculate the strength and direction of linear associations to understand their interdependencies within the waste-to-value conversion model. This analysis helps to identify how strongly the waste-to-value conversion indicators are associated with each other within the circular economy model. The correlation matrix is presented in Figure 3.

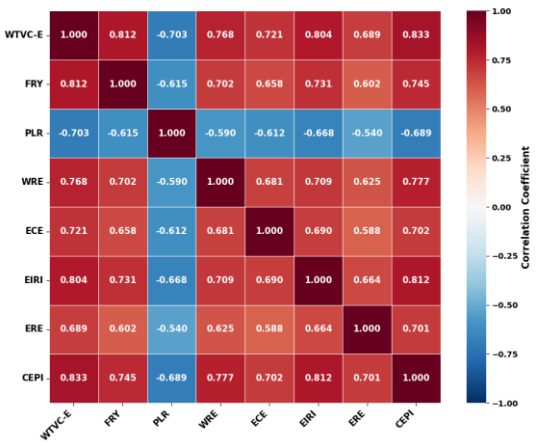


Figure 3. Visualization of correlation analysis outcome

Significant associations were observed among all variables ($p < 0.01$). WTVC-E displayed the strongest positive correlation with CEPI ($r = 0.833$), followed by FRY ($r = 0.812$) and EIRI ($r = 0.804$) is presented in Figure 3. PLR exhibited a robust negative relationship with WTVC-E ($r = -0.703$), highlighting its adverse influence.

5.4 Multiple Regression Analysis

Multiple regression analysis is applied to determine the combined and separate effects of multiple independent variables on the dependent variable (WTVC-E) to identify the most important predictors influencing waste-to-value conversion efficiency within the circular economy models. It was performed to estimate the association between dependent and independent variables. The regression output is presented in Table 4. In this analysis, B (unstandardized coefficient) represents the magnitude of change in the dependent variable for a one-unit change in the predictor, SE indicates the variability or precision of the estimated coefficient, β (standardized coefficient) represents the relative contribution and strength of each predictor in standardized form, and t-value measures the statistical significance of each predictor in the model.

Table 4. Multiple regression analysis identifying predictors of conversion efficiency

Variables	B	SE	β	t	p-value
FRY	0.284	0.041	0.312	6.95	<0.001
PLR	-0.221	0.038	-0.267	-5.82	<0.001
WRE	0.198	0.045	0.241	4.40	<0.001
ECE	0.176	0.049	0.198	3.59	<0.001
EIRI	0.251	0.043	0.276	5.84	<0.001
ERE	0.163	0.047	0.182	3.47	0.001
CEPI	0.312	0.040	0.338	7.80	<0.001
R^2=0.81, Adjusted R^2=0.80, F-statistic=102.4, p-value=<0.001					

coefficient of determination ($R^2 = 0.81$) indicated that 81% of the variability in WTVC-E was described by the independent variables included in the model. The adjusted R^2 value of 0.80 confirmed the stability of the model after accounting for predictor complexity. The overall regression model was *statistically significant* ($F = 102.4$, $p < 0.001$), representing strong predictive capability. Regression coefficient is shown in Figure 4.

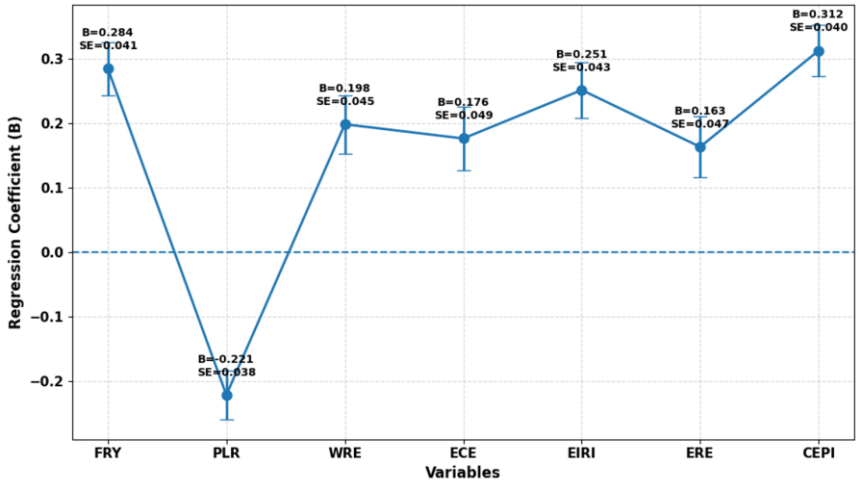


Figure 4. Visual representation of regression coefficient analysis

5.5 Chi-Square Test

Before applying the Chi-Square test, the continuous performance measures were classified into performance groups to determine the relationship patterns among sustainability and circular economy parameters. This classification process enabled us to identify dependency relations between the waste-to-value performance and other operational factors. Finally, the Chi-Square test was performed as an auxiliary statistical technique. It is used to examine whether significant associations exist among categorical forms of sustainability and circular economy performance variables within the waste-to-value conversion system. The test outputs are presented in Table 5. In this, Chi-Square value (χ^2) measures the magnitude of deviation between observed and expected distributions, the degrees of freedom (df) represent the number of independent categories used, p-value indicates the statistical significance.

Table 5. Chi-square test evaluating associations among sustainability performance variables

Variables	Chi-Square Value (χ^2)	df	p-value	Significance Level
FRY	52.64	4	$p < 0.001$	Significant
PLR	48.17	4	$p < 0.001$	Significant
WRE	45.89	4	$p < 0.001$	Significant
ECE	39.52	4	$p < 0.001$	Significant
EIRI	58.73	4	$p < 0.001$	Significant
ERE	41.36	4	$p < 0.001$	Significant
CEPI	61.28	4	$p < 0.001$	Significant

Table 5 indicated significant associations between WTVC-E and all explanatory variables ($p < 0.001$). The strongest relationship was observed between WTVC-E and CEPI ($\chi^2 = 61.28$), followed by EIRI ($\chi^2 = 58.73$) and FRY ($\chi^2 = 52.64$), confirming their importance in waste-to-value conversion performance. Figure 5 provides the pictorial representation of Chi-Square.

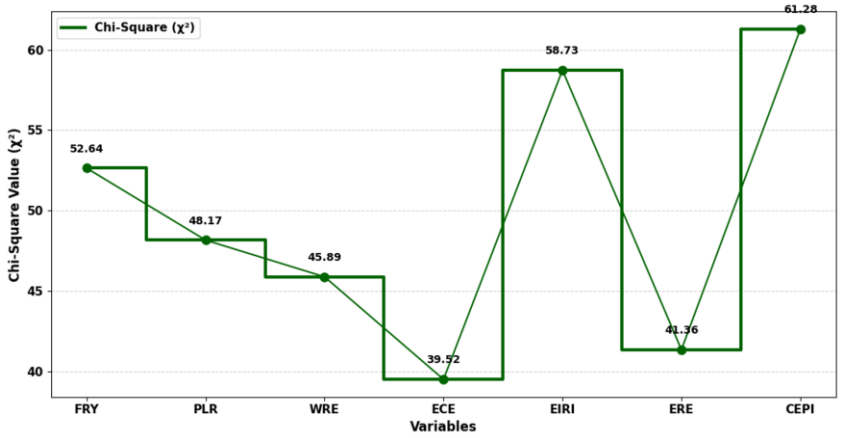


Figure 5. Chi-Square representation in a graphical format

5.6 Multicollinearity analysis

Multicollinearity analysis was performed to evaluate the degree of correlation among independent variables. Variance Inflation Factor (VIF) and Tolerance statistics were calculated for all predictors included in the regression model.

Table 6. Multicollinearity analysis outcomes for variables

Variable	Tolerance	VIF
FRY	0.52	1.92
PLR	0.48	2.08
WRE	0.61	1.64
ECE	0.69	1.45
EIRI	0.43	2.32
ERE	0.57	1.76
CEPI	0.39	2.56

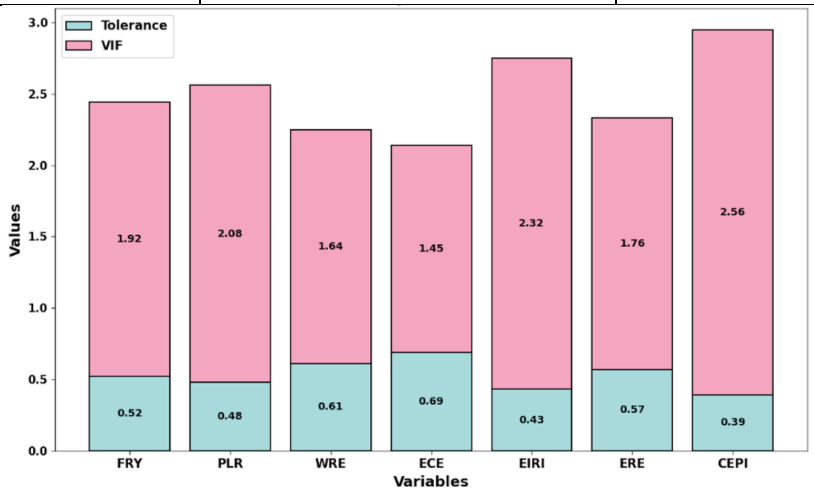


Figure 6. Graphical representation of multicollinearity analysis

The multicollinearity analysis results in Table 6 and Figure 6 indicate that all predictor variables satisfy the acceptable thresholds, with tolerance values surpassing 0.10 and VIF values remaining below 5.0. These outcomes confirm the absence of important multicollinearity among FRY, PLR, WRE, ECE, EIRI, ERE, and CEPI, ensuring the reliability and stability of the multiple regression model.

5.7 Material Flow Analysis (MFA) Results

MFA was used to analyze the systematic flow of paper waste materials throughout the process of recycling. The outcomes of MFA are presented in Table 7, which offers an overview of the material flows involved in the waste paper recycling process. The total input of waste paper amounted to 10.2 tons/day, where 6.8 tons/day of it was recovered in the form of reusable fibers. The 3.4 tons/day corresponded to the processing losses, linked to contaminants, moisture, and other non-recoverable components. As such, the achieved material recovery rate of 66.7% indicates the ability of the recycling process to keep significant amounts of materials inside the production cycle, thus decreasing the need for landfill sites.

Table 7. Material flow indicators for waste paper recycling system assessment

Indicator	Value
FRY	6.8 tons/day
PLR	3.4 tons/day
Total Waste Input	10.2 tons/day
Material Recovery Efficiency	66.7%

5.8 Life Cycle Assessment (LCA) Results

The LCA was performed to determine the environmental performance indicators in the recycling process. Environmental performance indicators that indicate to performance results are presented in Table 8, where WRE equals 71.28%, whereas EIRI amounts to 74.91%. ECE value is equal to 0.64, while CO_2 emissions have been decreased by 11.4 tons per month thanks to waste valorization activities.

Table 8. Environmental performance indicators from LCA research

Indicator	Value
WRE	71.28%
ECE	0.64
EIRI	74.91%
CO_2 Reduction	11.4 tons/month

5.9 Economic Sustainability Results

The financial assessment was done to determine financial sustainability indicators related to the recycling processes. Financial sustainability indicators that show the Economic Return Efficiency at 21.7% due to High income generation through recycling operations and cost savings are shown in Table 9. This positive net benefit shows that waste-to-value conversion contributes positively to the financial sustainability of the organization.

Table 9. Economic performance indicators of recycling sustainability analysis

Indicator	Value
ERE	21.7%
Cost Savings	High

Revenue from Recycling	High
Net Benefit	Positive

5.10 Circular Economy Performance Results

Circular economy performance was determined for the evaluation of the circular economy efficiency regarding recycling. Table 10 gives the results of circular economy performance assessment that indicated 0.76 for CEPI, implying that there were better performance indicators for circular economy. The recycling rate was found to be 78.4% and good waste diversion rate of 81.6% was identified.

Table 10. Circular economy performance indicators for recycling system efficiency

Indicator	Value
CEPI	0.76
Recycling Rate	78.4%
Resource Recovery Rate	73.1%
Waste Diversion Rate	81.6%

5.11 Discussion

The effectiveness of waste-to-value conversion efficiency process in the context of the model of circular economies has been examined in the present research to material recovery, environmental benefits, resource recovery, and economic success. As a result, it demonstrated high significance for the model of circular economies ($p<0.001$), which confirmed that the application of principles of circular economy makes an enormous contribution to increasing the level of WTVC-E. Based on the results obtained, it is possible to state that CEPI was the main variable that affects WTVC-E ($\beta = 0.338$, $p < 0.001$). The findings also suggest that FRY had a significantly positive effect ($\beta = 0.312$, $p < 0.001$), indicating that higher fiber recovery provides better resource recovery and recycling efficiency. Conversely PLR had a highly negative effect on WTVC-E ($\beta = -0.267$, $p < 0.001$), implying that losses of materials during recycling processes reduce overall conversion performance. This suggests the need to optimize resource recovery and limit process losses to make paper recycling systems sustainable and efficient. Traditional approaches have limitations such as [20] limit its focus to adsorption techniques for the treatment of leachates but do not analyze the conversion of waste into value in paper production. In a similar way, [22] relied on numerical simulation but failed to consider experimentation or industrial practice feasibility assessment. Research [27] did not explore the economic viability, scalability, and performance of the products from paper mill sludge. Further, [28] assessed the effectiveness of biosorbent techniques through controlled lab settings, without validating their application in real industrial wastewater systems. Moreover, [30] explored the efficiency of recycling process on a laboratory scale basis, without considering the practical losses associated with the recycling process. this research provides an all-round framework for measuring WTVC-E in the pulp and paper manufacturing sector where material recovery, performance of sustainability, circular economy, and economics are important. It assists in determining the critical elements that influence the efficacy of recycling, ensure resource conservation, minimize waste management, and guarantee sustainable industrial development. For practice, it is used to improve the efficacy of recycling, ensure resource conservation, minimize environmental harm, and increase economic gains from the effective use of a circular economy system.

6. Conclusion

The investigation of WTVC-E in paper industries was done in this research by evaluating resource recovery, circularity performance, environmental benefits, and economic sustainability outcomes. Data collection was done from fifteen factories for making paper, recycle centers, and waste collection units in one full year, providing N = 180

samples based on production data, waste recovery records, environmental monitoring, and financial performance statements. This methodology applied the use of MFA, LCA, Circularity Performance Assessment, and Economic Sustainability Assessment. The analysis of results was conducted through SPSS version 28. Descriptive statistics, Shapiro-Wilk test, Pearson correlation, multiple regression, and Chi-Square test have been used here. Outcomes showed that in Multiple Regression, CEPI was the strongest predictor of WTVC-E ($\beta = 0.338$, $t = 7.80$, $p < 0.001$); CEPI had the strongest positive correlation with WTVC-E ($r = 0.833$, $p < 0.01$); WTVC-E vs CEPI showed the highest Chi-Square association ($\chi^2 = 61.28$, $p < 0.001$); and CEPI demonstrated the highest normality value ($W = 0.981$, $p = 0.104$). The system produced an FRY of 6.8 tons/day, an EIRI of 74.91%, and an ERE of 21.7% demonstrating effective waste-to-value creation within a circular economy framework. Limitations include the dependency of the model based on the availability of information at hand from certain paper recycling plants, and lack of real time process control. The scope of future work should be towards intelligent optimization, digital twin modeling, and use of data from multiple regions.

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