

Article

Textile-Waste-Derived Biofuel Pellets for Coal Substitution: Combustion Emissions, Ash Characterization, Life Cycle of Carbon, and Economic Assessment

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Abstract

The increasing generation of textile cotton waste (TCW) and textile wastewater sludge (TWS) presents significant environmental management challenges. This study evaluates the conversion of TCW and TWS into biofuel pellets for waste recovery and coal substitution. Pellets were prepared at TWS ratios of 20:80, 40:60, 60:40, and 80:20 and assessed through combustion emission analysis, ash characterization, cradle-to-gate carbon assessment, and equal-energy cost comparison with imported bituminous coal. Increasing the TWS fraction prolonged combustion duration and increased SO₂ and NO_x emissions; however, all oxygen-normalized emissions remained within Sindh Environmental Quality Standards (SEQS) limits under the tested conditions. The 20:80 blend exhibited the lowest emission factors, with CO, SO₂, NO_x, and CO₂ emissions of 1.03 g kg⁻¹, 3.81 g kg⁻¹, 1.57 g kg⁻¹, and 1.42 kg kg⁻¹, respectively. Ash analysis showed that Cd and Pb were not detected, while measured heavy-metal concentrations remained below U.S. EPA regulatory limits and relevant EU limit values. The 20:80 pellet achieved a cradle-to-gate carbon intensity of 6.6 g CO₂e MJ⁻¹, approximately 59% lower than upstream coal production. Equal-energy fuel-cost savings relative to imported coal were 37.6% for the binder-based 20:80 pellet and 83.1% for the binder-free 40:60 pellet. Overall, the results indicate that TCW–TWS pellets, particularly those containing 20–40% TWS, can support textile waste utilization and partial coal substitution while reducing fuel costs.

Keywords: textile waste; biofuel pellets; combustion emissions; life-cycle assessment; techno-economic analysis; coal substitution



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1. Introduction

The textile sector generates substantial waste streams, including cotton-rich cutting residues, spinning waste, contaminated fibers, mixed textile waste, and wastewater treatment sludge. More than 92 million tons of textile waste are generated globally each year,

while low-value disposal routes contribute to environmental impacts [1]. In Pakistan, a recent survey-based study estimated annual textile waste generation at approximately 270,125 metric tons, including about 19,305 tons from Karachi [2], highlighting the need for improved waste-management and valorization strategies. Textile wastewater presents an additional burden because dyeing effluents may contain heavy metals, pigments, and chlorinated organic compounds that adversely affect aquatic environments [3]. Although circular-economy research in textiles has expanded, practical and technically validated valorization pathways for difficult industrial residues, particularly sludge and mixed processing wastes, remain limited [4].

Textile manufacturing generates two distinct waste streams, textile cotton waste (TCW) and textile wastewater sludge (TWS), arising from different production stages and requiring different management approaches. In a recent study, TCW, which is generated during cotton processing, spinning, fabric production, cutting, and finishing and mainly consists of short fibers, lint, yarn waste, fabric off-cuts, and fibrous dust, was converted into a high-fixed-carbon solid material [5]. In contrast, TWS is produced during physicochemical and biological treatment of textile effluents, concentrating suspended solids, dyes, salts, organic matter, metals, and treatment chemicals into dewatered sludge. Its variable, process-specific composition and typically high moisture, ash, salts, dye residues, and metal content can hinder direct combustion and complicate safe disposal [6]. Given these management challenges, the complementary characteristics of TCW and TWS provide a basis for their combined valorization. At the collection point, TCW and TWS contain approximately 10% and 85% moisture, respectively, highlighting the need for sludge pretreatment before combined valorization through drying, milling, pelletization, and thermal upgrading [7]. Unlike domestic wastewater sludge, the process-specific composition of TWS can result in low calorific value and a high ash content; however, blending with biomass or other organic wastes may improve fuel quality, combustion performance, and handling characteristics [8].

Thermal treatment can reduce sludge volume and recover energy, with performance influenced by blend chemistry, ash content, and combustion conditions. Thermal analysis of dyeing sludge–textile waste blends identified three co-combustion stages, confirming that textile waste alters sludge conversion pathways [9]. The study of textile dyeing sludge and waste biochar showed clear co-combustion synergy between 530 °C and 700 °C, demonstrating that during co-combustion, the total SO₂ emission can be reduced greatly, while the total NO emission can be increased. The reduction in SO₂ emissions is likely associated with sulfur retention in the ash through reactions with alkaline and alkaline-earth minerals, whereas the increase in NO emissions may result from enhanced conversion of fuel-bound nitrogen under improved combustion conditions and higher temperatures. This indicates that sulfur and nitrogen emissions can move in opposite directions when combustion performance is improved [10]. The same principle applies to the research on the production of sewage sludge briquettes, as sludge is required to be mixed with a lignocellulosic material, and combustion properties, pollutant emissions, and residue safety need to be assessed to determine the fuel quality [11]. The present study applies this integrated concept to TCW and TWS generated within the same industrial context, enabling a localized waste-to-energy pathway.

The main environmental issue of any sludge-derived solid fuel is emission behavior. Textile wastewater sludge can contain sulfur, nitrogen, chlorine, metals, and inorganic salts resulting from dyeing and finishing processes and wastewater treatment, which can lead to increased SO₂, NO_x, CO, and ash-related risks during combustion. Trace H₂S may also occur under localized oxygen-deficient or incomplete combustion conditions, despite the overall presence of oxygen. The heteroatoms in textile dyeing sludge, particularly N, S, and Cl, are a major technical challenge for sludge energy recovery, according to recent chemical-

looping combustion research on this type of sludge [12]. Studies of sulfur migration further show that waste-textile addition can alter, rather than merely dilute, sulfur conversion pathways and associated H_2S and SO_2 formation [13]. Similarly, direct measurements from landfill-gas cogeneration have shown that actual emissions of CO_2 , CO , NO_x , SO_2 , and particulate matter may differ from inventory-reported values, highlighting the importance of direct emission monitoring in waste-derived energy systems [14].

Ash quality is equally important because combustion transfers part of the inorganic risk to the solid residue. Textile wastewater sludge may contain trace metals such as Cr, Cu, Ni, Zn, As, Hg, Cd, and Pb, which can concentrate in fly and bottom ash during thermal treatment [15]. Incorporating sewage sludge by-products into thermal treatment products has been seen to stabilize heavy metals, and a recent environmental comparison of sewage sludge pyrolysis and incineration showed that thermal treatment by-products can be mobility and environmentally burdened if the by-product is ignored [16]. XRF and AAS have been used in bottom ash studies and have proven to be practical tools for correlating ash chemistry with environmental safety [17]. Therefore, TCW–TWS pellets should be evaluated not only for combustion performance but also for ash composition, heavy-metal risks, and safe disposal or reuse.

Environmental performance alone is insufficient to establish practical feasibility; LCA and TEA are needed to assess carbon intensity, production cost, energy value, and scale-up potential [18]. Wastewater-sludge valorization can recover biofuels and other products but may involve operational, economic, and environmental trade-offs [19]. Energy recovery from sludge can also reduce landfill dependence and support circular-economy objectives, particularly when fuel upgrading is applied [20]. Integrated LCA–TEA approaches have similarly been used to assess the environmental and economic viability of sludge co-conversion with other biomass feedstocks [21]. Therefore, TCW–TWS pellet studies should evaluate combustion performance alongside energy cost, carbon intensity, production cost, coal-substitution potential, annual savings, and payback period. In this context, economic feasibility can be assessed through alternative production scenarios, particularly binder-based and binder-free pathways, because binder addition may improve pellet integrity while increasing production costs, whereas binder-free formulations may offer cost advantages by eliminating external binder requirements.

Previous studies have largely addressed textile waste, sludge treatment, pelletization, combustion, ash safety, LCA, and economics separately. Despite growing interest in textile circularity, evidence remains limited for integrated recovery pathways that evaluate whole-system performance beyond general claims of circularity [22]. From a clean-technology perspective, converting TCW and TWS into solid biofuel pellets supports waste minimization, resource recovery, fossil-fuel substitution, and reduced environmental impacts in industrial applications.

The goal of this study is to evaluate the environmental and economic feasibility of converting TCW and TWS into solid biofuel pellets. The scientific novelty lies in the co-pelletization of these two distinct industrial textile waste streams and their integrated environmental and economic assessment, which has not been comprehensively addressed in previous studies. The assessment combines controlled combustion testing, oxygen-normalized and mass-based emission analysis, ash and heavy-metal characterization, cradle-to-gate carbon intensity, and equal-energy economic comparison with imported bituminous coal. This integrated approach assesses combined TCW–TWS biofuel pellets within a single industrial waste-to-energy pathway and identifies a practical TWS blending range of 20–40% based on emission performance, ash-related risks, carbon reduction, and economic feasibility.

2. Materials and Methods

2.1. Study Design and Methodological Framework

An integrated framework was used to evaluate biofuel pellets derived from textile cotton waste (TCW) and textile wastewater sludge (TWS), as illustrated in Figure 1. First, TCW and TWS were collected, pretreated, blended at selected ratios, and pelletized. The pellets were then characterized for fuel properties and combusted under controlled conditions. Flue-gas emissions were evaluated using oxygen-normalized concentrations and mass-based emission factors, while ash was characterized for elemental composition and heavy-metal-related risks. A cradle-to-gate carbon assessment quantified pellet production emissions, and a techno-economic analysis estimated production costs, coal-substitution savings, and payback. Finally, the environmental performance, energy characteristics, and economic feasibility of the selected pellet formulation were compared with imported bituminous coal on an equal-energy basis. The calculation equations were based on mass and energy balances, unit conversions, and engineering economic principles. The required experimental data were obtained from the present study, whereas external parameters, such as emission factors and specific equations, were adopted from the cited references, where applicable.

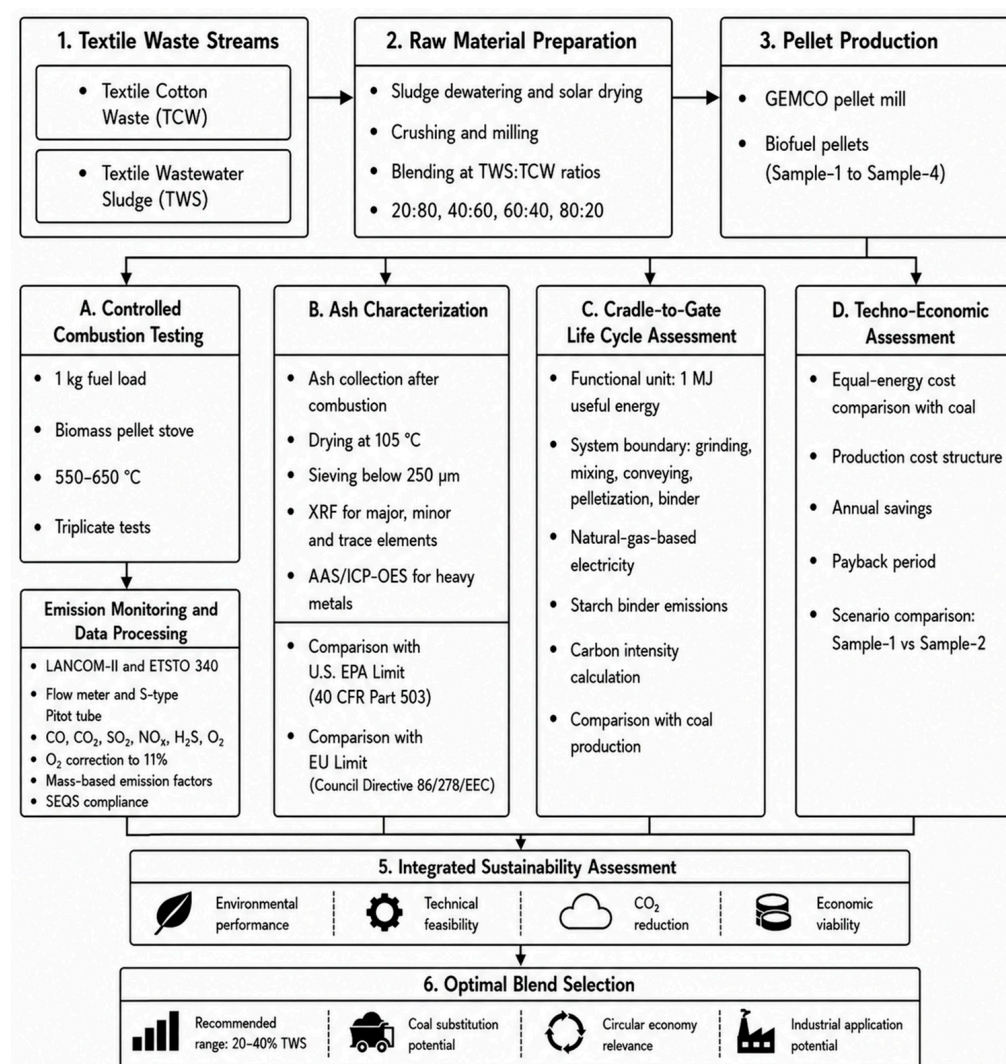


Figure 1. Methodological framework for the production and integrated environmental, combustion, and economic evaluation of TCW–TWS biofuel pellets.

2.2. Raw Material Collection and Preparation

The waste materials, TCW and TWS, were collected from AL-RAHIM TEXTILE INDUSTRIES, Nooriabad, Sindh, Pakistan. TCW originated from textile cutting and weaving operations, whereas TWS was recovered from the centrifuge output of the on-site effluent treatment plant treating textile process wastewater. At collection, TCW and TWS contained approximately 10% and 85% moisture, respectively. TWS was sun-dried in thin layers for approximately 6 days to about 10% moisture. Before pelletization, dried TWS was gently granulated and TCW was pre-shredded, followed by sequential screening through 5 and 3 mm meshes to obtain a particle size of ≤ 3 mm. The prepared feedstocks were stored in airtight containers under low-humidity conditions to minimize moisture reabsorption and variation.

The materials were blended on a mass basis at TWS ratios of 20:80, 40:60, 60:40, and 80:20, designated as Sample-1 to Sample-4, respectively, as summarized in Table 1. The blends were pelletized using a flat-die pellet mill to produce 8 mm diameter pellets and stored under dry conditions before combustion testing. Sample-1 contained 5 wt.% corn starch as a biodegradable binder to improve interparticle adhesion, pellet compactness, and handling durability. No external binder was required for the other formulations because their higher TWS contents provided sufficient binding during pelletization.

Table 1. TCW–TWS pellet formulation and sample coding.

Sample Code	TWS Fraction (%)	TCW Fraction (%)	TWS:TCW Mass Ratio	Assessment Role
Sample-1	20	80	20:80	Lowest-sludge formulation; selected as the most practically favorable binder-based case for LCA and economic assessment
Sample-2	40	60	40:60	Moderate-sludge formulation; evaluated as binder-free economic scenario
Sample-3	60	40	60:40	High-sludge formulation for emission trend assessment
Sample-4	80	20	80:20	Highest-sludge formulation for upper-limit emission assessment

Sample-1 was selected for the life-cycle assessment as the most favorable environmental case within the tested matrix, as it had the lowest TWS fraction and showed the lowest combustion emission factors under the tested stove conditions. This should not be interpreted as a universally optimal composition, because the preferred blend may vary with sludge characteristics, local emission limits, fuel prices, and available abatement technologies. Sample-2 was retained as a binder-free scale-up economic scenario because the 40:60 TWS blend exhibited sufficient natural binding. Thus, Sample-1 represented the low-emission binder-based pathway, whereas Sample-2 represented the lower-cost binder-free pathway.

2.3. Combustion Experimental Setup and Operating Protocol

Combustion experiments were conducted using a biomass pellet stove under controlled laboratory conditions. The combustion system consisted of a primary combustion chamber, a forced-draft air supply system, an exhaust outlet, and a vertically mounted stack for flue-gas sampling. Each experimental trial used a fixed fuel load of 1.0 kg of pellets. The burn cycle was divided into ignition, steady-state combustion, and burnout phases. Emission measurements were recorded during the steady-state combustion phase to reduce the influence of unstable ignition and late-stage burnout conditions. The combustion chamber

temperature during operation was maintained within approximately 550–650 °C. In this study, the term fixed air supply condition refers to maintaining the same forced-draft fan setting and primary air inlet position for all pellet formulations. Before the experimental runs, the air control setting was adjusted to achieve stable combustion and was then kept unchanged throughout all tests. No further adjustment of fan speed or air inlet opening was made during the steady-state emission-measurement period. The measured flue-gas O₂ concentration ranged from approximately 8 to 11%, reflecting differences in combustion behavior among pellet formulations under the same air control setting. Stack-gas velocity was measured separately for each formulation and used to calculate normalized velocity and dry flue-gas volume, as reported in Table 2. All blends were tested in triplicate to improve repeatability and to reduce random experimental variation.

Table 2. Stack parameters and calculated dry flue-gas volume.

Sample	Velocity (m s ^{−1})	Combustion Time (min)	Normalized Velocity (m s ^{−1})	V _{dry} (Nm ³ kg ^{−1})
Sample-1	7.87 ± 0.46	26 ± 2.65	4.45 ± 0.26	14.74
Sample-2	6.48 ± 0.57	32 ± 1.00	3.67 ± 0.32	14.94
Sample-3	5.32 ± 0.54	41 ± 2.65	3.01 ± 0.31	15.70
Sample-4	6.93 ± 0.74	44 ± 2.00	3.92 ± 0.42	21.96

Note: Values are reported as mean ± standard deviation from triplicate combustion tests (n = 3), where applicable. V_{dry} was calculated from the mean normalized velocity and mean combustion time according to Equation (1).

2.4. Stack Configuration, Flow Measurement and Dry Flue-Gas Volume Calculation

A vertically mounted stainless-steel stack was used for emission testing in order to minimize turbulence and sampling error. The sampling arrangement followed the general guidance of ISO 19867-1:2018 [23] for emission measurement from solid fuel combustion systems. The stack was 52 mm in inner diameter (which is equal to 0.052 m), and 2 m was the height from the stove outlet. The stack configuration was such as to provide a straight stack length of at least 8D (upstream) and 2D (downstream) from the sampling location (where D is the stack diameter). The sampling points were set to two flanged sampling points 90° apart for representative sampling. During testing, the stack-gas temperature was approximately 210 °C (483 K). Gas velocity was measured using a certified electronic flow meter together with an S-type Pitot tube and normalized to standard temperature conditions. The dry flue-gas volume per kilogram of fuel was determined by Equation (1) [24,25]:

$$V_{dry} = \frac{Q_N \times t}{m_f} \quad (1)$$

where V_{dry} is the dry flue-gas volume per kilogram of fuel (Nm³/kg), t is the combustion time (s) and m_f is the burnt fuel mass (kg). A fuel mass of 1.0 kg was used for each test. Detailed stack-area, velocity normalization, and volumetric flow calculations are provided in Supplementary Section S1.

2.5. Emission Monitoring, Calibration and Quality Assurance

In order to enhance accuracy and to provide a cross-check, two certified analyzers were employed for monitoring flue-gas emissions. Combustion gases were measured by using a LANCOM-II Digital Flue Gas Analyzer (Make: LANCOM; Model: LANCOM-II; Serial No.: 298997). The analyzer covered the following measurement ranges: CO 0–2000 ppm, CO₂ 0–25% vol, SO₂ 0–2000 ppm, NO 0–1000 ppm, NO₂ 0–100 ppm, H₂S 0–200 ppm, and O₂ 0–25% vol. Emissions were also monitored and cross-checked using a portable flue-gas analyzer of the type TESTO 340 (Serial No.: 60968702). Before testing, all the

emission monitoring instruments were calibrated by the ISO Accreditation Laboratory, namely Alpha Calibration Pvt. Ltd. Calibration was done under controlled laboratory conditions at a temperature of 23 ± 2 °C and a relative humidity of $50 \pm 10\%$. Calibration gases used included BRISTOL Certified, ISO 17025/NIST [26] traceable gases. High-purity nitrogen/synthetic air was used for zero calibration of both analyzers prior to each test session. A Certified Electronic Flow Meter from TSI Trust Science Innovation USA (NIDT-Air Products) was used to measure the velocity and volumetric flow rate of the stack gas. Calibration data showed accurate performance of about ± 0.1 – 0.2 L/min over the flow range tested from 1 to 10 L/min. Using the calibrated flow meter and S-type Pitot tube together, the stack-gas velocity was determined, and subsequently dry flue-gas volume and mass-based emission factors were calculated.

2.6. Oxygen Normalization and Emission Factor Calculation

CO₂, CO, SO₂, NO, NO₂, H₂S, and O₂ were monitored. NO_x was determined from NO and NO₂ and reported as NO₂ equivalent. To account for oxygen dilution and excess air, measured dry-gas concentrations were normalized to 11% O₂ using Equation (2) [24]:

$$C_{11\%O_2} = C_{\text{measured}} \times \frac{21 - 11}{21 - O_2} \quad (2)$$

where $C_{11\%O_2}$ is the concentration at an 11% oxygen condition, C_{measured} is the measured dry gas concentration and O_2 is the measured oxygen concentration in the flue gas. The number 21 is the concentration of oxygen in the air. After ppm-to-mass conversion, mass-based emission factors were calculated using Equation (3) [23,24]:

$$EF_{g/kg} = \frac{C_m \times V_{dry}}{1000} \quad (3)$$

where C_m is the mass concentration (mg/Nm³) and V_{dry} is the dry flue-gas volume (Nm³/kg fuel). The CO₂ emission factor was calculated from the CO₂ mass concentration and dry flue-gas volume. Detailed NO_x aggregation, ppm-to-mass conversion, and intermediate emission-factor calculations are provided in Supplementary Section S2.

2.7. Ash Sampling, Elemental Characterization and Heavy-Metal Risk Assessment

The ash from the TCW-TWS pellets was gathered after each burn cycle from complete combustion. All ash samples were left to cool to room temperature in a laboratory under contamination-free conditions. Cooled ash was oven dried at 105 °C to remove moisture, homogenized and sieved to less than 250 µm for analysis.

X-ray Fluorescence Spectroscopy (XRF) was used to determine the elemental composition of the ash using an Energy Dispersive X-ray Fluorescence (EDXRF) spectrometer (EDX-8100). Major and trace elements analyzed by XRF were Fe, Ca, Si, P, S, Mn, Sr, Cr, Zn, Cu, Ni, Ba, Rb and Zr. To ensure good homogeneity and analytical consistency, finely ground ash samples were pelletized using hydraulic pressure before being measured by EDXRF. According to the manufacturer's guideline for a light-element matrix, the approximate lower detection limits of the EDX-8100 for the relevant elements evaluated in this study were 1 ppm for Fe, Ca, Mn, and Ba and 0.1 ppm for Sr, Br, Rb, and Zr. These values represent manufacturer-specified guideline detection limits. Heavy metals were acid-digested and quantified by Atomic Absorption Spectrometry (AAS) and/or Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) due to their environmental significance. About 0.5 g of the ash was digested using concentrated nitric acid (HNO₃) and hydrochloric acid (HCl) under controlled heating. The digested solution was filtered, diluted with deionized water to a known volume and analyzed for Hg, As, Cd, Pb, Cr, Cu,

Ni and Zn using calibrated multi-element standards. Elemental and heavy-metal analyses were conducted as single determinations for each representative sample. Measured concentrations of heavy metals were compared with regulatory limits for land application of biosolids set by the U.S. EPA [27] to ensure environmental compliance and assess ash safety. The routine gravimetric ash-content equation is provided in Supplementary Section S3.

2.8. Cradle-to-Gate Life-Cycle Assessment Framework

A screening-level cradle-to-gate carbon assessment was performed for the practically favorable formulation under the tested conditions (Sample-1) to estimate the upstream greenhouse gas (GHG) emissions associated with pellet production. The assessment followed the general principles and framework of ISO 14040 and ISO 14044 [27,28]; however, it should not be interpreted as a full ISO-compliant cradle-to-grave life-cycle assessment. Instead, it provides an indicative environmental screening of the pellet production stage. The functional unit was defined as 1 MJ of useful energy to enable comparison between the developed biofuel pellets and conventional coal on an equivalent energy basis. The environmental impact assessment focused on Global Warming Potential (GWP), expressed as kg CO₂ equivalent.

The system boundary, illustrated in Figure 2, included grinding, natural solar drying of textile wastewater sludge, mixing, conveying, pelletization, and starch binder production. Combustion-phase emissions and ash disposal were placed outside the cradle-to-gate system boundary because combustion emissions were experimentally quantified and discussed separately in this study, while the objective of the present assessment was limited to upstream GHG emissions associated with pellet production.

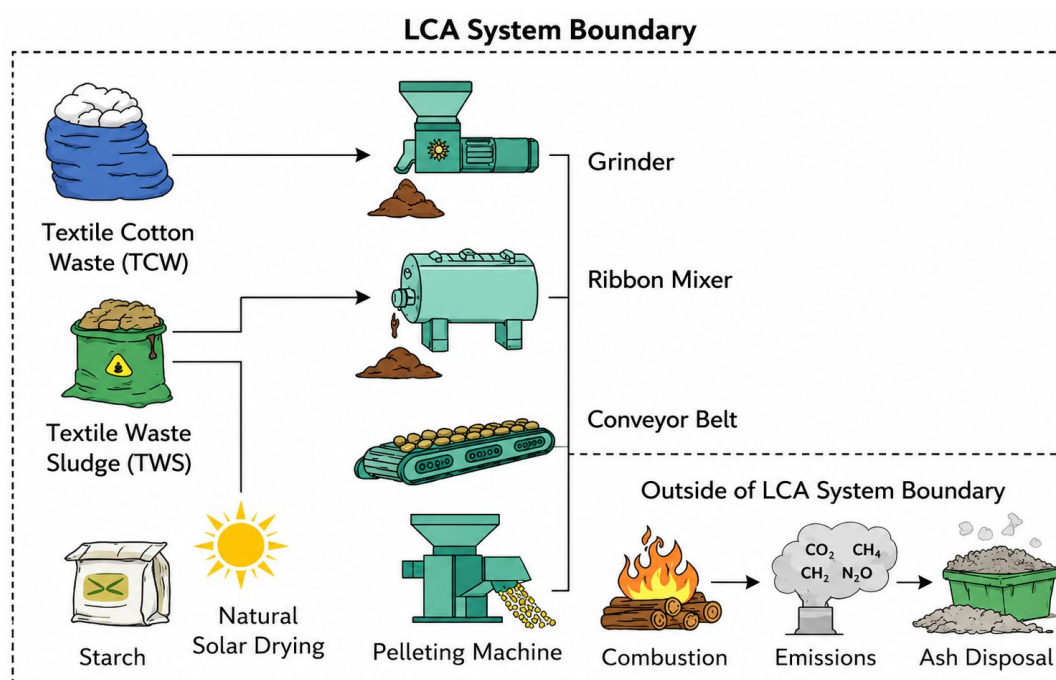


Figure 2. Cradle-to-gate LCA system boundary for TCW-TWS pellet production, showing included production processes and excluded downstream stages.

Textile cotton waste (TCW) and textile wastewater sludge (TWS) were treated as industrial by-products using a cut-off allocation approach. TCW is generated as an unavoidable by-product during weaving and towel shearing operations, whereas TWS is continuously produced during the routine operation of a textile wastewater treatment plant as sludge cake requiring disposal. Both materials are generated as part of normal textile manufac-

turing and wastewater treatment operations regardless of whether pellet production is undertaken. Therefore, no upstream environmental burdens associated with their original generation were assigned to the pellet system. Only the additional processing required to convert these by-products into biofuel pellets was included in the assessment. Transportation emissions were considered negligible because the feedstocks were generated, processed, and utilized within the same industrial facility.

Accordingly, comparisons with coal presented in this study should be interpreted as indicative screening-level results within the defined cradle-to-gate boundary rather than definitive cradle-to-gate environmental comparisons.

The overall global warming potential (GWP) was calculated using Equation (4) [28,29]:

$$GWP = \sum_{i=1}^n (Activity\ Data_i \times Emission\ Factor_i) \quad (4)$$

Electricity for pellet production was supplied by a natural-gas generator with a measured gas-consumption rate of 0.28 m³/kWh. The natural-gas emission factor used was 0.05444 kg CO₂ per standard cubic foot (SCF) from the Environmental Protection Agency of the United States [27]. Sample-1 contained 5 wt.% starch; a starch production emission factor of 1.1 kg CO₂e/kg starch was adopted from the BAFA dataset in Climatiq [30]. The total cradle-to-gate carbon footprint per kilogram of pellet was calculated using Equation (5) [28,29]:

$$CF_{\text{pellet}} = E_{\text{process}} + E_{\text{binder}} \quad (5)$$

The cradle-to-gate carbon intensity per unit energy was calculated using Equation (6) [29]:

$$CI_{\text{pellet}} = \frac{CF_{\text{pellet}}}{Energy_{\text{pellet}}} \quad (6)$$

For indicative comparison, an upstream coal-production intensity of 16.22 g CO₂/MJ was adopted from Yang, Dou et al. [31]. Comparisons with coal should therefore be interpreted as screening-level results within the defined cradle-to-gate boundary. The percentage reduction relative to coal was determined by the use of Equation (7) [29]:

$$\text{Reduction (\%)} = \frac{CI_{\text{coal}} - CI_{\text{pellet}}}{CI_{\text{coal}}} \times 100 \quad (7)$$

Calculations for specific energy consumption (SEC), natural-gas consumption, emission-factor conversion, binder emission, and energy-unit conversion are provided in Supplementary Section S4.

2.9. Techno-Economic Assessment and Equal-Energy Cost Analysis

The techno-economic assessment was done to compare TCW–TWS biofuel pellets and imported bituminous coal on an equal-energy basis. The reference fuel used was China imported bituminous coal. The coal price was USD 116/ MT (or USD 0.116/kg), and the gross calorific value of the coal was 5768 kcal/kg. The moisture and ash content of the reference coal was 7.8% and 16.4%, respectively. The gross calorific value of the binder-based Sample-1 pellet was 3377 kcal/kg, and the gross calorific value of the binder-free Sample-2 scenario was 2968 kcal/kg.

Following established techno-economic assessment approaches for bioenergy and waste-derived fuel systems [18,21], the comparison was conducted using energy-equivalent fuel quantities, unit fuel costs, cost savings, and simple payback indicators. The energy-equivalent biofuel cost was calculated as

$$C_{\text{biofuel,eq}} = M_{\text{biofuel,eq}} \times C_{\text{biofuel}} \quad (8)$$

The percentage saving relative to coal was calculated as

$$\text{Saving (\%)} = \frac{C_{\text{coal}} - C_{\text{biofuel,eq}}}{C_{\text{coal}}} \times 100 \quad (9)$$

Saving per kilogram of coal replaced was calculated as [18,21]

$$S_{\text{kg}} = C_{\text{coal}} - C_{\text{biofuel,eq}} \quad (10)$$

The simple payback period was determined as [18]

$$SPB = \frac{I_{\text{capital}}}{S_{\text{annual}}} \quad (11)$$

Two economic scenarios were analyzed. The formulation with 20:80 TWS:TCW (Sample-1) was binder-based, and the formulation with 40:60 TWS:TCW (Sample-2) was binder-free. The same equal-energy approach was used for both scenarios and coal with the aim of making an economic comparison based on energy delivered not just on coal mass. Detailed energy-ratio derivations, equivalent pellet-mass calculations, cost-per-million-kcal calculations, and daily/monthly/annual saving conversions are provided in Supplementary Section S5.

2.10. Pellet Production Cost Estimation

Pellet production cost included energy, labor, binder, depreciation and maintenance, and TCW raw-material costs, minus the avoided sludge-disposal credit. Total capital investment was USD 9392 for a production capacity of 200 kg/h. Two operators were required, each with a monthly salary of USD 178.89. A 26-working-day month was assumed. For Sample-1, starch was used at 5 wt.% at USD 0.358/kg. Equipment life was assumed to be 5 years, corresponding to 20% annual depreciation, while the annual maintenance cost was USD 537 based on the recommended parts-replacement schedule. TCW represented 80% of Sample-1 feedstock at USD 0.018/kg. The avoided TWS disposal cost was USD 0.054/kg, based on the actual industrial rate paid for the disposal of textile wastewater sludge at a landfill site during the study period.

The final net production cost was calculated as [18,21]

$$C_{\text{net}} = C_{\text{energy}} + C_{\text{labour}} + C_{\text{binder}} + C_{\text{fixed}} + C_{\text{TCW}} - \text{Credit}_{\text{TWS}} \quad (12)$$

The same cost framework was applied to Sample-1 and the binder-free Sample-2 scenario. Detailed component equations for electricity cost, monthly and annual production, binder cost, depreciation, fixed cost, TCW cost, and sludge-disposal credit are provided in Supplementary Section S6.

All combustion data was presented on a dry basis and reduced to 273 K and 1 atm. Emission concentrations measured were first converted to 11% O₂, then to mass concentrations, and finally to mass-based emission factors per kg of fuel. NO_x was reported on a NO₂ equivalent basis. Elements of ash and heavy metals were measured in mg/kg or ppm and compared to U.S. EPA regulations. To facilitate equitable comparisons between pellets and coal, results from both the life cycle and economic perspectives were normalized to 1 MJ of useful energy, whereas the results from the economic perspective were also expressed on an equal-energy basis.

3. Results

3.1. Combustion Operating Conditions and Dry Flue-Gas Volume

The operating results indicate that combustion characteristics varied as the TWS content increased. The compositions and fuel properties of the pellet samples are summarized in Table 2. Velocity, combustion time, and normalized velocity are reported as mean $\pm$ standard deviation (SD) from triplicate combustion tests ($n = 3$). The shortest combustion time of 26 min was recorded in Sample-1 with 20% TWS and 80% TCW showing comparatively faster and more stable combustion under the fixed air supply condition. Increasing the TWS up to 40% did not significantly disturb the combustion flow pattern, as Sample-2 had a slightly longer combustion time of 32 min and a similar dry gas volume of 14.94 Nm³/kg. Sample-3 and Sample-4 had a combustion time of 41 min and 44 min, respectively, and the volume of dry flue-gas produced per kg of samples was maximum in the case of Sample-4 (21.96 Nm³/kg). This suggests that the presence of high sludge retards the burn cycle and consequently the total gas production, probably due to the increased ash content and inorganic fraction in TWS. The observed standard deviations indicate generally low-to-moderate variability among the triplicate tests, suggesting reasonable repeatability under the tested stove configuration and operating conditions. The results showed that the combustion time was more controlled in the 0.2–0.4 TWS range compared to 0.6–0.8 TWS, which led to more flue-gas production.

3.2. Emission Performance of TCW–TWS Pellets

3.2.1. Measured Flue-Gas Concentrations at Actual Oxygen Basis

The measured flue-gas concentrations at the actual oxygen basis are presented in Table 3. The measured concentrations indicate a clear trend of an increase in most gaseous pollutants as the amount of TWS in the pellet blend increased. All measured flue-gas concentrations are reported as mean $\pm$ standard deviation (SD) from triplicate combustion tests ($n = 3$). CO levels rose from 71 ppm (Sample-1) to 119 ppm (Sample-4), and due to the greater sludge content, the combustion completeness was slightly less. SO₂ rose significantly from an initial 115 ppm to 349 ppm, indicating that TWS added more sulfur compounds than TCW. The NO_x also rose from 66 ppm to 228 ppm, indicating a higher contribution of fuel-bound nitrogen from sludge-rich blends. H₂S rose from 3 ppm to 7 ppm, and although they are low compared to SO₂, the combustion atmosphere was still as a whole largely in the oxidizing area. The concentration of CO₂ was high in Sample-3 (6.93%) and low in Sample-4 (5.30%), which could be due to the difference in combustion duration and oxygen dilution and fuel composition. The observed variability across triplicate tests was generally low to moderate for the major flue-gas components, indicating reasonable repeatability under the tested stove configuration and combustion conditions. It can be seen that the higher TWS fractions resulted in higher pollutant formation, and Sample-1 and Sample-2 emissions were comparatively cleaner.

Table 3. Measured flue-gas concentrations at the actual oxygen basis for the tested pellet samples.

Sample	O ₂ (%)	CO (ppm)	CO ₂ (%)	SO ₂ (ppm)	NO _x (ppm)	H ₂ S (ppm)
Sample-1	8.3 $\pm$ 0.26	71 $\pm$ 3.79	6.22 $\pm$ 0.29	115 $\pm$ 12.49	66 $\pm$ 10.79	3 $\pm$ 1.00
Sample-2	9.1 $\pm$ 0.21	84 $\pm$ 2.65	6.72 $\pm$ 0.41	166 $\pm$ 13.50	109 $\pm$ 13.45	5 $\pm$ 1.00
Sample-3	9.1 $\pm$ 0.20	92 $\pm$ 4.58	6.93 $\pm$ 0.19	253 $\pm$ 5.00	155 $\pm$ 14.00	5 $\pm$ 1.00
Sample-4	9.8 $\pm$ 0.71	119 $\pm$ 11.15	5.30 $\pm$ 0.14	349 $\pm$ 36.50	228 $\pm$ 6.56	7 $\pm$ 1.00

Note: Values are reported as mean $\pm$ standard deviation (SD) from triplicate combustion tests ($n = 3$).

3.2.2. Oxygen-Normalized Emissions and SEQS Compliance

The oxygen-normalized emissions (11% O₂) are presented in Table 4, while their comparison with the Sindh Environmental Quality Standards (SEQS) is illustrated in Figure 3. All of the pellet blends were below the SEQS limits for CO, SO₂, NO_x and H₂S after normalization to 11% O₂. CO was found to be increasing from 55.9 ppm in Sample-1 to 106.3 ppm in Sample-4, but even the highest concentration was well below the SEQS limit of 800 ppm. SO₂ rose from 90.6 ppm to 311.6 ppm (below the set limit of 1700 ppm) and NO_x rose from 52.0 ppm to 203.6 ppm (below 1200 ppm). H₂S rose from 2.36 ppm to 6.25 ppm, which is still under the limit of 10 ppm. All samples were compliant, but the trend of higher SO₂ and NO_x values with higher TWS content indicates that regulatory compliance alone may not be sufficient for identifying a practically favorable pellet blend under the tested conditions. Sample-1 and Sample-2 provided better balance between emission control and sludge utilization, and Sample-4 had the highest level of acid gas and NO_x emissions, although they were still below the allowable limits. However, the practically favorable blend range may vary depending on local emission limits, site-specific sludge characteristics, fuel prices, and the availability and effectiveness of emission-abatement technologies.

Table 4. Emissions normalized to 11% O₂.

Sample	CO (ppm)	CO ₂ (%)	SO ₂ (ppm)	NO _x (ppm)	H ₂ S (ppm)
Sample-1	55.9	4.90	90.6	52.0	2.36
Sample-2	70.6	5.65	139.5	91.6	4.20
Sample-3	77.3	5.82	212.6	130.3	4.20
Sample-4	106.3	4.73	311.6	203.6	6.25

Note: Concentrations normalized to 11% O₂ were calculated from the corresponding mean measured concentrations and mean O₂ values using Equation (2).

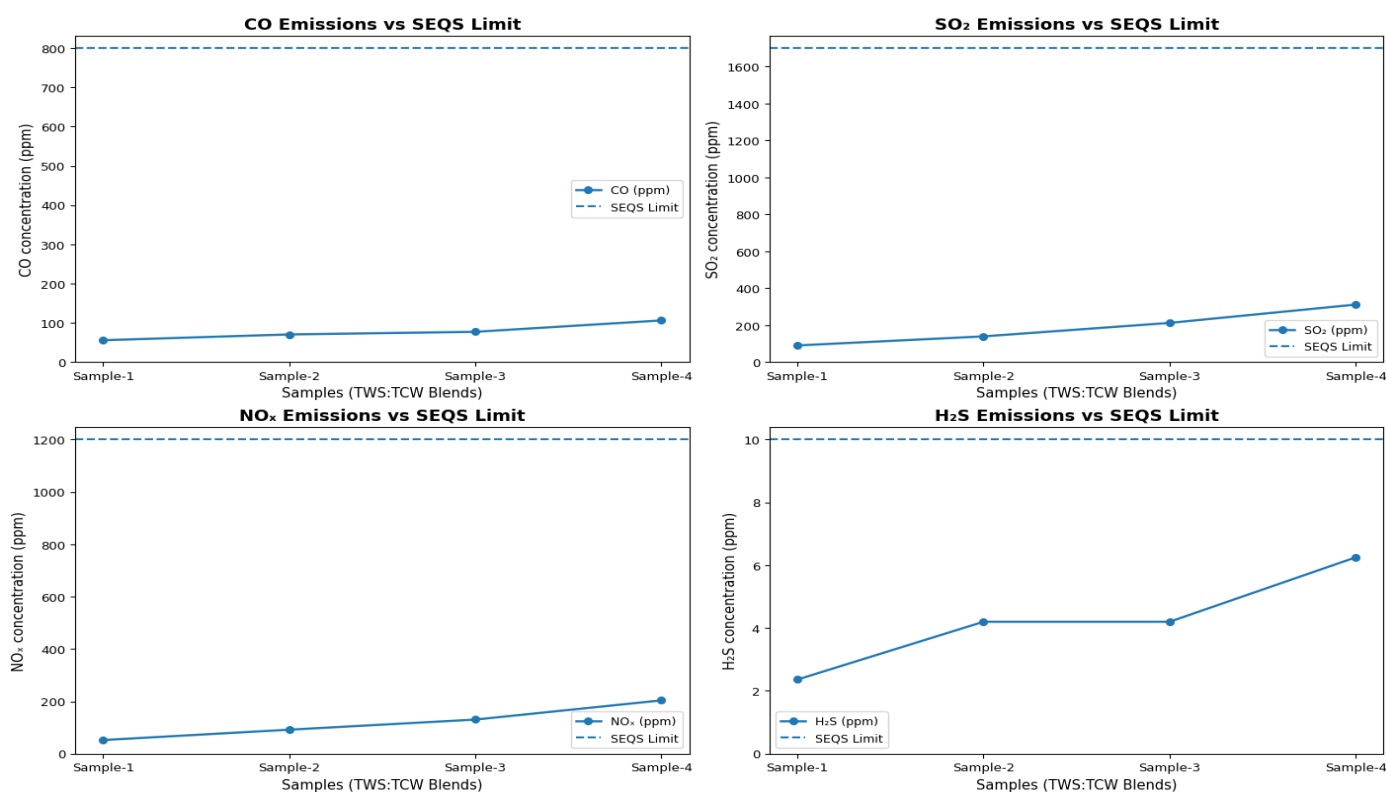


Figure 3. Oxygen-normalized flue-gas pollutant concentrations of TCW:TWS pellets at 11% O₂ compared with SEQS limits.

3.2.3. Mass-Based Emission Factors

The final mass-based emission factors normalized to 11% O₂ are presented in Table 5. The results of emission factors reveal that the pollutant emission per kg of fuel was directly influenced by TWS content. CO level increased from 1.03 g/kg in Sample-1 to 2.92 g/kg in Sample-4 and confirmed that with the increase in the sludge blending ratio, combustion completeness decreased without causing severe incomplete combustion. The biggest growth was found in SO₂, which increased from 3.81 g/kg to 19.56 g/kg, indicating that the sulfur-containing compounds in TWS were the primary source of the acid gas generation. The NO_x rose from 1.57 g/kg to 9.18 g/kg, which shows that the nitrogen in the sludge fuel was a significant source of NO_x. The concentration of H₂S was still lower than SO₂, and the range of concentration was from 52.9 mg/kg to 208.7 mg/kg, which can be interpreted as that the sulfur was mainly oxidized to SO₂ under the given combustion conditions. The addition of more CO₂ (from 1.42 kg/kg to 2.04 kg/kg) was partly due to the longer combustion duration and the higher dry flue-gas volume in sludge-rich blends. Sample-1 had the cleanest combustion profile overall; Sample-2 was acceptable and could use more sludge; and Sample-3 and Sample-4 complied but were less acceptable because they had a higher formation of SO₂ and NO_x.

Table 5. Final mass-based emission factors at 11% O₂.

Sample	CO (g kg ^{−1})	SO ₂ (g kg ^{−1})	NO _x (g kg ^{−1})	H ₂ S (mg kg ^{−1})	CO ₂ (kg kg ^{−1})
Sample-1 (20:80)	1.03	3.81	1.57	52.9	1.42
Sample-2 (40:60)	1.32	5.96	2.81	95.5	1.66
Sample-3 (60:40)	1.52	9.54	4.20	100.3	1.80
Sample-4 (80:20)	2.92	19.56	9.18	208.7	2.04

3.3. Effect of Sludge Blending Ratio on Pollutant Formation

The overall emission trend indicates that the TWS fraction was the dominant factor leading to the formation of pollutants in TCW–TWS pellets. TCW is primarily composed of lignocellulosic material and hence has a stable combustion profile due to the presence of a higher combustible organic fraction in the waste, whereas TWS has higher amounts of ash, sulfur, nitrogen, inorganic salts, and textile processing chemicals. The reason for these increasing emissions with an increasing sludge ratio was the differences in composition. There was a slight increase in CO levels indicating a progressive decrease in the oxidation efficiency with an increase in the amount of sludge. SO₂ rose most sharply, indicating that sludge sulfur had significant impact on the acid gas production. NO_x also showed a steady rise, showing that fuel-bound N was converted into NO_x during combustion. H₂S concentration was relatively low and indicated a satisfactory oxidizing environment for combustion. Within the tested stove configuration and combustion conditions, the 20–40% TWS blending range showed a comparatively favorable balance between emission performance and sludge valorization.

It should be emphasized that the combustion and emission results obtained in this study are specific to the tested small-scale biomass stove configuration, 1 kg batch fuel loading, and investigated combustion temperature range of 550–650 °C. Differences in burner aerodynamics, gas residence time, excess air conditions, heat-transfer characteristics, and combustion scale may significantly influence emission behavior in industrial boilers, furnaces, and process heating systems. Therefore, direct extrapolation of the present emission results to industrial-scale applications should be considered speculative, and dedicated pilot- or industrial-scale combustion trials are required to validate performance under such operating conditions.

3.4. Ash Composition and Environmental Safety Assessment

3.4.1. Major and Trace Element Composition by XRF

The major and trace element concentrations in the raw materials and pellet ash determined by XRF are presented in Table 6. According to the XRF results, the ash is primarily Fe, Ca and Si dominated, and the feedstock ratio significantly affects the elemental profile of the ash. The concentration of Fe in the raw sludge was very high (116,400 mg/kg), which accounts for the high level of Fe in the pellet ash containing sludge; it increased from 32,400 mg/kg in Sample-1A to 67,300 mg/kg in Sample-4A. The highest concentration of Ca was found in raw cotton (80,700 mg/kg); thus, the alkaline mineral fraction of the ash was greatly contributed by TCW. Pellet ash contained 13,300–25,200 mg/kg of Ca, which may have a certain liming value when using the ash in land application. Silicon was found to be higher in the sludge-rich blends (Sample-4A, 17,000 mg/kg) as compared to the other samples (Sample-1A, 4900 mg/kg), suggesting that the inorganic mineral content was higher in the sludge-rich blends. The ash content of the pellets contained between 2100 and 3900 mg/kg of phosphorus and between 5800 and 8800 mg/kg of sulfur. Other minor elements like Mn and Sr occurred at a low concentration, and Br, Rb, Ba and Zr were not detected or negligible in most of the samples of pellet ash. The ash composition indicates stable mineral characteristics, and no abnormal enrichment of hazardous trace elements was detected in the XRF profile.

Table 6. Major and trace element concentrations in raw materials and pellet ash by XRF (mg kg^{−1} or ppm).

Element	Raw Sludge	Raw Cotton	Sample-1A (20:80)	Sample-2A (40:60)	Sample-3A (60:40)	Sample-4A (80:20)
Fe	116,400	15,300	32,400	64,500	63,900	67,300
Ca	25,700	80,700	13,300	20,900	21,000	25,200
Si	8200	0	4900	10,900	16,300	17,000
P	5800	24,500	2100	2100	3500	3900
S	13,000	6900	5800	8800	6500	6400
Mn	1700	0	500	1000	800	900
Sr	600	800	100	300	300	400
Br	0	800	60	0	0	0
Rb	0	200	0	0	0	0
Ba	0	1100	0	0	0	0
Zr	20	0	0	0	0	0

3.4.2. Toxic Heavy Metals and Comparison with Regulatory Limits

The heavy-metal concentrations in the raw materials and combustion ash, together with their comparison with selected U.S. EPA 40 CFR Part 503 and EU Council Directive 86/278/EEC limits, are presented in Table 7. Heavy-metal concentrations in the pellet ash samples were compared with selected U.S. EPA limits and EU limit values for sludge use in agriculture under Council Directive 86/278/EEC. Chromium concentrations in pellet ash ranged from 200 to 500 mg/kg; however, no corresponding Cr benchmark was available in the selected regulatory limits. Copper concentrations ranged from 100 to 200 mg/kg, below the selected EU range of 100–1750 mg/kg and the U.S. EPA limit of 4300 mg/kg. Nickel concentrations ranged from 0 to 30 mg/kg, below the EU range of 300–400 mg/kg and the U.S. EPA limit of 420 mg/kg. Zinc was detected only in Sample-1A at 60 mg/kg,

below the EU range of 2500–4000 mg/kg and the U.S. EPA limit of 7500 mg/kg. Arsenic concentrations ranged from 2.97 to 6.91 mg/kg and remained below the selected U.S. EPA limit of 75 mg/kg, while no corresponding EU value was available in the selected benchmark. Mercury was detected only in the raw sludge at 0.047 mg/kg and was not detected in any pellet ash samples. Cadmium and lead were also not detected in any pellet ash samples. Overall, based on total heavy-metal concentrations, the pellet ashes were below the selected U.S. EPA and EU benchmark values where corresponding limits were available. However, these comparisons should not be interpreted as direct regulatory approval for land application, which would require further evaluation of leaching behavior, pH, salinity, nutrient availability, and agronomic suitability.

Table 7. Heavy-metal concentrations in raw materials and combustion ash compared with U.S. EPA 40 CFR Part 503 and EU Council Directive 86/278/EEC limits.

Metal	EU Limit (mg kg ^{−1})	U.S EPA Limit (mg kg ^{−1})	Raw Sludge	Raw Cotton	Sample-1A (20:80)	Sample-2A (40:60)	Sample-3A (60:40)	Sample-4A (80:20)	Comparison
Cr	—	—	700	0	200	400	500	500	No Benchmark
Cu	1000–1750	4300	300	200	100	200	200	200	Within limit
Ni	300–400	420	50	0	30	10	0	0	Within limit
Zn	2500–4000	7500	0	200	60	0	0	0	Within limit
Hg	16–25	57	0.047	ND	ND	ND	ND	ND	Within limit
As	—	75	9.93	1.50	2.97	3.61	5.54	6.91	Within limit
Cd	20–40	85	ND	ND	ND	ND	ND	ND	Within limit
Pb	750–1200	840	ND	ND	ND	ND	ND	ND	Within limit

ND = Not detected.

3.5. Cradle-to-Gate Life-Cycle Performance

3.5.1. Electricity Consumption During Pellet Production

The electricity inventory for TCW–TWS pellet production is summarized in Table 8. From the electricity inventory it is seen that 200 kg pellets were produced by using 14.42 kWh of electricity, which is a specific electricity consumption of 0.0721 kWh/kg. The electricity consumption was dominated by the pelleting machine, which consumed 6.80 kWh per 200 kg or 47.16% of the total electricity consumption. This identifies palletization as the main energy hotspot in the production process. The second largest consumer was the ribbon mixer with 25.80% (3.72 kWh), followed by the grinder with 14.56% (2.10 kWh) and conveyor belt with 12.48% (1.80 kWh). This indicates that the primary processing steps that have an impact on production energy demand are mechanical densification and mixing. No external thermal drying load was assumed for sludge drying, which was done by natural exposure to the sun, and this helped in reducing the upstream carbon burden of pellet production.

Table 8. Electricity inventory for TCW–TWS pellet production.

Process Stage	Electricity per 200 kg (kWh)	Specific Electricity (kWh kg ^{−1})	Share of Total Electricity (%)
Grinder	2.10	0.0105	14.56
Ribbon mixer	3.72	0.0186	25.80
Conveyor belt	1.80	0.0090	12.48
Pelleting machine	6.80	0.0340	47.16
Total	14.42	0.0721	100.00

3.5.2. GHG Emission Components, Carbon Intensity and Coal Comparison

The cradle-to-gate GHG emission components, pellet carbon intensity, and comparison with the coal reference are summarized in Table 9. Cradle-to-gate assessment revealed that the total upstream emissions of Sample-1 were 0.0938 kg CO₂e/kg of pellets, which included 0.0388 kg CO₂e/kg of pellets from natural-gas-based electricity generation and 0.0550 kg CO₂e/kg of pellets from starch binder production. The starch binder contributed a larger share of upstream GHG emissions than process electricity, indicating that binder production is an important contributor to the cradle-to-gate carbon footprint of the developed pellets. The pellet carbon intensity was calculated based on the pellet GCV of 3377 kcal/kg (14.13 MJ/kg) and was 6.6 g CO₂e/MJ. The screening-level cradle-to-gate assessment indicates that the developed pellets exhibited a lower upstream carbon intensity than the coal reference (16.22 g CO₂e/MJ), primarily due to the utilization of waste-derived feedstocks, natural solar drying, and localized pellet production. However, this comparison should be interpreted as an indicative upstream comparison within the defined cradle-to-gate system boundary rather than a definitive cradle-to-grave environmental assessment.

Table 9. Cradle-to-gate GHG emission components, pellet carbon intensity and coal comparison.

Component/Parameter	Calculation Basis	Value/Emission Contribution
Natural-gas-based electricity emissions	$0.0202 \text{ m}^3 \text{ gas/kg} \times 1.92 \text{ kg CO}_2/\text{m}^3$	0.0388 kg CO ₂ e/kg pellet
Starch binder emissions	$5 \text{ wt.\%} \times 1.1 \text{ kg CO}_2\text{e/kg starch}$	0.0550 kg CO ₂ e/kg pellet
Total cradle-to-gate pellet emissions	Electricity emissions + binder emissions	0.0938 kg CO ₂ e/kg pellet
Pellet GCV	Given value for Sample-1	3377 kcal/kg
Pellet energy content	3377×0.004184	14.13 MJ/kg
Pellet carbon intensity	$0.0938/14.13$	0.0066 kg CO ₂ e/MJ
Converted pellet carbon intensity	kg to g conversion	6.6 g CO ₂ e/MJ
Coal production carbon intensity	Coal mining and processing before combustion	16.22 g CO ₂ e/MJ
Indicative reduction relative to coal (upstream basis)	$[(16.22 - 6.6)/16.22] \times 100$	≈59%

Note: The coal carbon intensity is presented as an indicative upstream reference for comparison within the defined cradle-to-gate system boundary only.

3.5.3. Sensitivity Analysis

The results of the sensitivity analysis are summarized in Table 10. To evaluate the robustness of the screening-level cradle-to-gate carbon assessment, a one-at-a-time (OAT) sensitivity analysis (±20%) was performed. The two principal upstream inventory parameters, namely electricity-related emissions and the starch binder emission factor, were varied independently, while all other inventory data remained unchanged. These parameters

were selected because they represent the major upstream contributors to the total GHG emissions associated with pellet production. The results showed that the pellet carbon intensity varied between 5.86 and 7.42 g CO₂e/MJ, compared with the base-case value of 6.64 g CO₂e/MJ (Table 10). The starch binder emission factor exhibited a slightly greater influence on total GWP than electricity-related emissions due to its larger contribution to upstream emissions. Although the absolute GWP varied under the assumed uncertainty scenarios, the relative environmental trend remained unchanged. Under all tested sensitivity scenarios, the pellet-production-stage carbon intensity remained below the referenced upstream coal-production intensity of 16.22 g CO₂e/MJ, corresponding to an indicative reduction range of approximately 54.3–63.9% relative to the upstream coal reference. This comparison should be interpreted as indicative and limited to the defined upstream system boundary. Overall, the results indicate that the conclusions of this screening-level cradle-to-gate assessment are reasonably robust within the assumed $\pm 20\%$ variation range.

Table 10. Sensitivity analysis of cradle-to-gate GHG emissions under $\pm 20\%$ variation of key inventory parameters.

Scenario	Electricity-Related Emissions (kg CO ₂ e/kg Pellet)	Starch Binder Emissions (kg CO ₂ e/kg Pellet)	Total GWP (kg CO ₂ e/kg Pellet)	Carbon Intensity (g CO ₂ e/MJ)
Base case	0.0388	0.0550	0.0938	6.64
Electricity-related emissions (+20%)	0.0466	0.0550	0.1016	7.19
Electricity-related emissions (−20%)	0.0310	0.0550	0.0860	6.09
Starch binder emission factor (+20%)	0.0388	0.0660	0.1048	7.42
Starch binder emission factor (−20%)	0.0388	0.0440	0.0828	5.86

3.5.4. Feedstock Variability and Site-Specific Applicability

The TCW and TWS investigated in this study were obtained from a single textile manufacturing facility; therefore, the findings should be interpreted as site-specific. Although the case-study facility uses textile processing chemicals and auxiliaries managed under the ZDHC chemical management framework, TCW and TWS composition may vary across facilities due to differences in raw materials, dye systems, chemical formulations, wastewater treatment practices, and sludge dewatering conditions. In particular, variations in Cr, Cu, other trace metals, inorganic salts, and sulfur- or nitrogen-containing constituents could influence ash safety and gaseous emission profiles. Therefore, direct extrapolation of the present findings to other textile facilities or regions is not recommended without preliminary site-specific physicochemical and elemental characterization of the feedstocks.

3.6. Techno-Economic Performance and Coal-Substitution Potential

3.6.1. Pellet Production Cost Structure and Cost Contribution

The operating cost breakdown and cost contribution for Sample-1 pellet production are summarized in Table 11. Based on the cost structure, the final net production cost for Sample-1 was 0.042 USD/kg. The starch binder cost was the highest, accounting for 0.0179 USD/kg or about 43% of the total production cost. The next biggest contributors were energy at 0.0083 USD/kg (around 20%) and labor at 0.0081 USD/kg (around 19%). The depreciation and maintenance cost was 0.0045 USD/kg, and the net material adjustment (after accounting for TCW cost and sludge-disposal credit) was around 0.0036 USD/kg.

This identifies the starch binder as the primary cost contributor, thereby justifying the evaluation of the binder-free Sample-2 formulation.

Table 11. Operating cost breakdown and cost contribution for Sample-1 pellet production.

Cost Component	Unit Basis	Cost (USD/kg)	Approximate Contribution
Energy	0.0721 kWh/kg at 0.12 USD/kWh	0.0083	~20%
Labor	Two operators; monthly production basis	0.0081	~19%
Starch binder	5% material input	0.0179	~43%
Depreciation + maintenance	Capital recovery	0.0045	~11%
Subtotal operating cost	—	0.0390	—
Textile cotton waste	80% raw material	+0.0143	—
Sludge utilization credit	20% disposal avoided	−0.0107	—
Net material adjustment	TCW cost – sludge credit	0.0036	~7%
Final net production cost	—	0.042	100%

3.6.2. Fuel Characterization and Equal-Energy Cost Comparison

The fuel characteristics and equal-energy economic comparison between coal and Sample-1 pellets are presented in Table 12. From the equal-energy comparison, it was observed that the GCV of Sample-1 is less than the coal (3377 kcal/kg as against 5768 kcal/kg), and 1708 kg of pellets was required to replace the energy supplied by 1000 kg of coal. On an equal-energy basis, the fuel cost decreased from USD 116.00 for 1000 kg of coal to USD 72.43 for the required 1708 kg of Sample-1 pellets. This resulted in an energy saving of 37.6% and a net saving of 43.57 USD. The useful-energy cost also decreased with coal at 20.11 USD/Mkcal and for Sample-1 at 12.56 USD/Mkcal, which means that even when considering the lower calorific value, the pellet remained economically attractive on an equal-energy basis.

Table 12. Fuel characteristics and equal-energy economic comparison.

Parameter	Imported Coal	Sample-1 Biofuel Pellet
GCV (kcal/kg)	5768	3377
Moisture (%)	7.8	10.1
Ash (%)	16.4	10.3
Unit cost (USD/kg)	0.116	0.042
Quantity on equal-energy basis (kg)	1000	1708
Total cost on equal-energy basis (USD/MT of coal)	116.00	72.43
Net saving compared with coal (USD/MT of coal)	—	43.57
Equal-energy saving (%)	—	37.6
Cost per million kcal (USD/Mkcal)	20.11	12.56
Cost reduction per Mkcal (%)	—	~37.5

Note: Cost calculations were performed using unrounded values; displayed unit costs are rounded for presentation.

3.6.3. Productivity, Annual Savings and Payback Period

The financial performance indicators for Sample-1 pellet production are summarized in Table 13. The economic indicators indicate that Sample-1 is economically feasible at the selected production scale. The saving per kilogram of coal replaced was approximately USD 0.044, resulting in a daily saving of USD 44; the monthly saving was USD 1144, and the annual saving was USD 13,728. With a total capital investment of USD 9392 and an annual net benefit of USD 13,728, the system showed a simple payback period of approximately 8.2 months. The reported economic indicators are based on the actual coal price (USD 116/t) at the time of the study, the production cost estimated under the present operating conditions, and the avoided sludge-disposal cost considered in the base-case scenario. Therefore, the calculated savings and payback period should be interpreted as indicative economic outcomes. Actual economic performance may vary depending on future coal price fluctuations, production scale, financing costs, and regional operating conditions. This recovery time indicates that TCW–TWS pellet production can be economically attractive for industrial users, particularly where avoided sludge-disposal costs and coal substitution provide additional economic benefits. The results indicate that coal substitution, combined with avoided sludge-disposal costs and rapid capital recovery, is the primary driver of the economic feasibility rather than the low production cost alone.

Table 13. Financial performance indicators for Sample-1 pellet production.

Indicator	Value
Saving per kg coal replaced	0.044 USD
Saving per day	44 USD
Saving per month	1144 USD
Saving per year/annual net benefit	13,728 USD
Capital investment	9392 USD
Simple payback period	8.2 months

The avoided sludge-disposal credit was considered because textile wastewater sludge (TWS) generated during routine operation of the wastewater treatment plant is required to be disposed of through an authorized (EPA-certified) disposal contractor at an approved landfill site in accordance with the applicable environmental regulations. Therefore, utilization of TWS as a pellet feedstock avoids the associated disposal cost under the base-case scenario adopted in the present study.

3.6.4. Binder-Based and Binder-Free Scenario Comparison

The equal-energy comparison of the binder-based (Sample-1) and binder-free (Sample-2) pellet scenarios is presented in Table 14. Sample-2 has a lower GCV of 2968 kcal/kg, as compared to Sample-1 with 3377 kcal/kg, and thus more mass of Sample-2 has to be used to replace coal energy. Specifically, Sample-2 needs 1.943 kg to replace 1 kg of coal, while Sample-1 requires 1.708 kg. The production cost of Sample-2 is, however, much lower at 0.0101 USD/kg, as it does not need a starch binder, whereas Sample-1 is 0.042 USD/kg. On an equal-energy basis, the cost of Sample-2 is calculated to be only 0.0196 USD per kg coal replaced, while for Sample-1, it is 0.072 USD. This leads to an improvement in the saving per kg of coal replaced and the corresponding equal-energy saving from 0.044 USD in Sample-1 to 0.0964 USD in Sample-2 and from 37.6% to approximately 83.1%. Sample-1 exhibited better environmental performance, whereas Sample-2 demonstrated stronger economic performance due to the elimination of the starch binder, which substantially reduced the production cost. Accordingly, the reported equal-energy savings of 37.6% for

Sample-1 and approximately 83.1% for Sample-2 represent indicative economic outcomes under the conditions adopted in the present study and may vary with future changes in coal prices, production scale, financing costs, and operating conditions.

Table 14. Equal-energy comparison of binder-based and binder-free pellet scenarios.

Indicator	Sample-1 Binder-Based (20:80)	Sample-2 Binder-Free (40:60)
GCV (kcal kg ^{−1})	3377	2968
Production cost (USD kg ^{−1})	0.042	0.0101
Energy ratio relative to coal	0.5855	0.5146
Biofuel required per kg coal (kg)	1.708	1.943
Equal-energy cost (USD kg ^{−1} coal equivalent)	0.072	0.0196
Saving per kg coal replaced (USD)	0.044	0.0964
Equal-energy saving (%)	37.6	≈83.1
Simple payback period	8.2 months	≈3.7 months

3.6.5. Economic Uncertainty and Scenario Analysis

The results of the screening-level economic uncertainty and scenario analysis for Sample-1 are summarized in Table 15. The base-case economic results reflect the actual industry operating conditions and site-specific cost data used in this study. To examine scenario dependence, a screening-level analysis was conducted using $\pm 20\%$ variations in the coal price and Sample-1 pellet production cost, together with 50% and zero sludge-disposal-credit cases. A 20% decrease in coal price reduced the equal-energy saving from 37.6% to approximately 22.0%, whereas a 20% increase raised it to approximately 48.0%. Similarly, a $\pm 20\%$ variation in pellet production cost changed the saving to approximately 50.0% and 25.1%, respectively. Under 50% and zero sludge-credit cases, the saving decreased to approximately 29.7% and 21.8%, respectively, but remained positive at the adopted coal price (Table 15).

Table 15. Screening-level economic uncertainty and scenario analysis for Sample-1.

Scenario	Coal Price (USD/t)	Sample-1 Cost (USD/kg)	Equal-Energy Saving (%)
Base case	116.0	0.0424	37.6
Coal price −20%	92.8	0.0424	22.0
Coal price +20%	139.2	0.0424	48.0
Pellet production cost −20%	116.0	0.0339	50.0
Pellet production cost +20%	116.0	0.0509	25.1
50% sludge-disposal credit	116.0	0.0478	29.7
Zero sludge-disposal credit	116.0	0.0531	21.8

The results confirm that the reported savings are sensitive to coal price, pellet production cost, and realization of the avoided sludge-disposal benefit. Potential off-site ash-management costs, where applicable, would further reduce the net benefit. Scale effects and financing costs were not explicitly modeled because reliable scale-up functions and project-specific financing parameters were unavailable; therefore, the reported payback periods represent simple undiscounted indicators. Accordingly, the savings of 37.6% for Sample-1 and approximately 83.1% for Sample-2 should be interpreted as indica-

tive outcomes under the evaluated industry conditions rather than universally applicable economic findings.

3.7. Integrated Sustainability Assessment and Practically Favorable Range Under the Tested Conditions

The integrated results indicate that TCW–TWS biofuel pellets are technically viable, show potential environmental benefits, and may offer economic advantages for partial substitution of imported bituminous coal under the tested conditions. All pellet blends complied with the SEQS limits after normalization to 11% O₂, while pollutant formation increased with sludge concentration, particularly for SO₂ and NO_x. This indicates that higher TWS ratios improve sludge utilization but may also require greater attention to emission control. Ash characterization revealed that Fe, Ca, and Si were the predominant ash-forming elements in the pellets, while the measured concentrations of harmful heavy metals remained below the U.S. EPA and EU limits used for comparison. Furthermore, Cd and Pb were not detected in the pellet ash, and Hg was not detected in the final ash samples. The screening-level cradle-to-gate assessment indicated lower upstream carbon intensity for Sample-1 than the referenced coal-production value, and this trend remained robust under the $\pm 20\%$ sensitivity scenarios. Based on the base-case economic analysis using actual industry operating conditions and site-specific cost data, the equal-energy fuel cost was 37.6% lower for Sample-1, with an estimated annual saving of USD 13,728 and a simple payback period of 8.2 months. Across the evaluated economic sensitivity scenarios, the equal-energy saving for Sample-1 ranged from approximately 21.8% to 50.0%, confirming that the economic outcome remained positive but varied with coal price, pellet production cost, and realization of the avoided sludge-disposal benefit. The binder-free Sample-2 scenario showed approximately 83.1% equal-energy savings due to its lower production cost. Overall, the 20–40% TWS blending range provided a favorable balance among emission control, waste valorization, ash safety, upstream carbon performance, and economic performance under the tested conditions. Sample-1 showed the most favorable overall environmental performance under the evaluated conditions, whereas Sample-2 offered the strongest economic potential for scale-up.

4. Discussion

The combustion results show that TCW–TWS pellets are a viable solid fuel, and the textile wastewater sludge content definitely influenced the combustion behavior. The combustion time was found to be shortest in Sample-1 with 20% TWS and 80% TCW (26 min) and highest in Sample-4 with 80% TWS (44 min), and the dry flue-gas volume was found to be maximum in Sample-4 with 80% TWS (21.96 Nm³ kg^{−1}) and minimum in Sample-1 (14.74 Nm³ kg^{−1}). This trend indicates that the pellets with the presence of sludge burned slower and produced more flue gas, which is attributed to the higher ash, mineral and inorganic content in TWS. This result is consistent with Ansari et al. [7], who found that the quality of TCW–TWS pellets is significantly influenced by the feedstock conditioning, blending, pellet size and torrefaction conditions. Gadhi et al. [6] also found that textile sludge can be processed to make fuel pellets, and the combustible value is better when mixed with another fuel with higher combustible value. It was found that the textile waste causes the dyeing-sludge combustion to undergo light volatile, heavy volatile, and char-burning stages, and it favors a longer combustion time observed for the sludge-rich samples [9]. In addition, a thermal conversion study conducted by Tujjohra et al. [5] demonstrated that cotton-rich textile waste exhibits a high thermal conversion potential, further emphasizing the stability of the TCW-rich blends. The 20–40% TWS range seems

to be more appropriate for stable combustion, whereas the 60–80% TWS range extends combustion duration and gas production.

The emission profile indicates that with an increase in sludge content, the emissions of most pollutants, particularly SO_2 and NO_x , have increased. CO concentration rose from 1.03 g kg^{-1} in Sample-1 to 2.92 g kg^{-1} in Sample-4, indicating that combustion was less complete at higher levels of TWS. The sulfur- and nitrogen-bearing compounds in TWS were found to be the key contributors to the formation of acid gases and NO_x as the concentrations of SO_2 and NO_x increased significantly from 3.81 g kg^{-1} to 19.56 g kg^{-1} and 1.57 g kg^{-1} to 9.18 g kg^{-1} , respectively. However, the concentration of H_2S was still significantly lower than that of SO_2 , increasing from 52.9 mg kg^{-1} to 208.7 mg kg^{-1} , indicating that the combustion environment was largely oxidizing. The researchers Jiang et al. [12] pointed out that nitrogen, sulfur, and chlorine pollutants are significant issues during the combustion of textile dyeing sludge. Huang et al. [10] also found that there is a co-combustion synergy between the textile dyeing sludge and waste biochar, but S and N emissions do not always go down together. Khan et al. [32] also observed that textile sludge has bioenergy potential; however, before industrial application, the behavior of pollutants and residues must be assessed to evaluate the potential for thermal conversion. All oxygen-normalized emissions in the present results were below SEQS limits, but Sample-1 and Sample-2 were more environmentally balanced by complying with lower SO_2 and NO_x formation.

The ash findings add to the environmental acceptability of the pellets, as no hazardous enrichment was seen in the tested pellet ash. The XRF analysis revealed that ash was rich in Fe, Ca and Si. The concentration of Fe increased with the sample from $32,400 \text{ mg kg}^{-1}$ in Sample-1A to $67,300 \text{ mg kg}^{-1}$ in Sample-4A, and the concentration of Si increased from 4900 mg kg^{-1} to $17,000 \text{ mg kg}^{-1}$, indicating that the sludge was a major source of the mineral-rich fraction of ash. Ca was also detected in all the pellet ash samples, where the concentration was found to be between $13,300$ and $25,200 \text{ mg kg}^{-1}$, indicating that TCW contributed to the alkaline ash fraction. Heavy-metal results were more significant for safety: Cr, Cu, Ni, Zn, Hg, As, Cd and Pb were all below U.S. EPA and EU limits values; Cd and Pb were not detected in pellet ash; and Hg was detected in raw sludge at 0.047 mg kg^{-1} but not in final pellet ash. The safe heavy-metal profile in the present study is a strong finding, as the sludge co-combustion ash may be ecologically hazardous if heavy metals concentrate in the residue, as indicated by Yu et al. [15]. Lee et al. [16] also emphasized the need to consider end-of-life effects of by-products in thermal sludge studies. Debrah and Dinis [17] demonstrated the need for ash characterization, as it can lead to a secondary risk if it is not disposed of properly. Liu et al. [33] also found that pollutant emissions and the migration of metals can be affected by sludge co-combustion. The conclusion of these studies is that TCW–TWS pellet ash is not hazardous within the limits tested but should be agronomically validated for land application.

The cradle-to-gate assessment indicates a lower upstream carbon intensity for Sample-1 than the referenced coal-production value within the defined screening-level system boundary. Total upstream emissions were $0.0938 \text{ kg CO}_2\text{e kg}^{-1}$ pellet, of which $0.0388 \text{ kg CO}_2\text{e kg}^{-1}$ was associated with natural-gas-based electricity generation and $0.0550 \text{ kg CO}_2\text{e kg}^{-1}$ with starch binder production. This indicates that starch binder production contributed more to upstream GHG emissions than process electricity. Gierowicz et al. [34] also identified the production stage as a major environmental hotspot in the life cycle of waste-derived products, with electricity consumption during processing contributing substantially to environmental impacts. With a GCV of $3377 \text{ kcal kg}^{-1}$, equal to 14.13 MJ kg^{-1} , the base-case pellet carbon intensity was $6.64 \text{ g CO}_2\text{e MJ}^{-1}$. This was lower than the referenced upstream coal-production intensity of $16.22 \text{ g CO}_2\text{e MJ}^{-1}$ reported by Yan et al. [31], corresponding to an indicative base-case reduction of approx-

imately 59%. Under the $\pm 20\%$ sensitivity scenarios, the pellet carbon intensity ranged from 5.86 to 7.42 g CO₂e MJ⁻¹, corresponding to an indicative reduction range of approximately 54.3–63.9% relative to the upstream coal reference. These comparisons are limited to the defined upstream system boundary and should not be interpreted as comprehensive cradle-to-grave environmental comparisons. Osman et al. [18] highlighted the importance of life-cycle assessment and techno-economic analysis for bioenergy systems, as process inputs can alter the actual sustainability outcomes. Similarly, Mohamed et al. [21] reported the importance of integrated environmental evaluation for sewage sludge and biomass co-pyrolysis. Hammar et al. [35] also demonstrated that circular textile pathways need to be evaluated using well-defined system boundaries. Thus, the current screening-level assessment indicates a potential upstream carbon benefit under the defined boundary while also identifying starch binder production as an important hotspot and an opportunity for both cost and carbon reduction.

The techno-economic results revealed that the pellets were still competitive even after making the correction to lower calorific value. Coal had a GCV of 5768 kcal kg⁻¹ and cost 0.116 USD kg⁻¹, while Sample-1 had a GCV of 3377 kcal kg⁻¹ and cost 0.042 USD kg⁻¹. As Sample-1 was lower in energy density, 1708 kg of pellets was required for replacing 1000 kg of coal energy. Despite this equal-energy conversion, the cost of the fuel still fell from 116.00 USD for coal to 72.43 USD for Sample-1, which resulted in a saving of 43.57 USD or a base-case saving of 37.6% of the energy cost for coal. The unit price of energy also fell, from 20.11 USD/Mkcal (coal) to 12.56 USD/Mkcal (Sample-1). Across the evaluated economic sensitivity scenarios, the equal-energy saving for Sample-1 ranged from approximately 21.8% to 50.0%, indicating that the economic advantage remained positive but varied with coal price, pellet production cost, and the realization of the avoided sludge-disposal benefit. This is due to the cost structure: starch binder cost was approximately 43%, energy 20%, labor 19% and depreciation 11% of the production cost. Sample-2 was more economically viable due to the largest cost driver being the binder. Sample-2 had a lower GCV of 2968 kcal kg⁻¹ and, therefore, 1.943 kg of it was required to be equivalent to 1 kg of coal, but the cost of Sample-2 was 0.0101 USD kg⁻¹ (no binder), which brought the equal-energy cost to 0.0196 USD kg⁻¹ coal equivalent and savings to an indicative value of approximately 83.1% under the evaluated conditions. These findings are consistent with previous studies demonstrating that the viability of waste-derived fuels should be assessed through both fuel performance and economic feasibility [6,7,18,21]. Similarly, recent biogas research has shown that the practical implementation of renewable-energy projects depends on integrating economic feasibility with environmental, infrastructural, and site-specific considerations [36].

The results support the choice of a most practical blending range of 20–40% TWS. Considering all the aspects mentioned above, Sample-1 was environmentally superior, as it had the lowest emission factors, safe ash, and lowest SO₂ and NO_x levels and cradle-to-gate carbon intensity of 6.6 g CO₂e MJ⁻¹. Sample-2 was economically better due to the fact that there was an elimination of the binder, which decreased production cost and increased equal-energy savings to almost 83.1%. This compromise is in line with the current research on the circular economy, which indicates that waste valorization must be a compromise between environmental safety, process performance and adoption cost. Shamsuzzaman et al. [37] found that the research on textile waste management focuses on the circular-economy approach, and there is a lack of measurable evidence of the performance of the system for recovery. Similarly, Saha et al. [4] reported that circular textile research requires more than just sustainability statements at the technology level. Biyada and Urbonavičius [1] noted that the challenge of textile waste circularity is ongoing. Chang and Shen [8] also reported that converting textile wastewater sludge into solid

recovered fuel represents a waste-to-energy pathway. TCW–TWS pellets therefore represent a practical solution to textile waste disposal by reducing reliance on coal, supporting compliance with emission regulations, maintaining acceptable ash quality, decreasing upstream GHG intensity, and enabling relatively rapid cost recovery. TCW–TWS pellets represent a practical solution to the problem of textile waste disposal, reducing the reliance on coal, ensuring compliance with emissions regulations, ensuring proper ash quality, decreasing GHG intensity upstream, and ensuring quick cost recovery.

5. Conclusions and Implications

This study indicates the potential environmental and economic feasibility of converting textile cotton waste (TCW) and textile wastewater sludge (TWS) into solid biofuel pellets for partial coal substitution. A key contribution of this study is the co-pelletization of two distinct textile waste streams and their integrated assessment through combustion performance, emissions, ash and heavy-metal characterization, screening-level carbon assessment, and equal-energy economic comparison. Blend composition strongly influenced performance: cotton-rich formulations showed better combustion behavior and lower emissions, whereas higher TWS fractions increased combustion duration and SO₂ and NO_x emissions. Under the tested conditions, all pellet blends remained within SEQS emission limits, while ash analysis showed no detectable Cd or Pb and measured heavy metals remained below the U.S. EPA and EU limits used for comparison.

The 20:80 TWS pellet achieved a base-case screening-level cradle-to-gate carbon intensity of 6.64 g CO₂e MJ^{−1}, with a sensitivity range of 5.86–7.42 g CO₂e MJ^{−1}. Equal-energy analysis indicated base-case fuel-cost savings of 37.6% for the binder-based 20:80 pellet and approximately 83.1% for the binder-free 40:60 pellet relative to imported coal. For the 20:80 pellet, scenario analysis showed that the equal-energy saving remained positive, ranging from approximately 21.8% to 50.0% under the tested variations in coal price, pellet production cost, and sludge-disposal credit. Overall, a TWS content of 20–40% represents a practically favorable range under the tested conditions, balancing emission performance, ash-related risks, carbon reduction, and economic feasibility.

Further pilot-scale and industrial boiler trials are required to confirm pellet durability, storage behavior, combustion-system compatibility, long-term emissions, and ash management. Future work should also address ash leaching, binder optimization, scale-up of binder-free production, and cradle-to-grave life-cycle assessment.

Supplementary Materials: The following are available online at <https://www.mdpi.com/article/10.3390/environments13070402/s1>, Section S1: Detailed stack-flow and dry flue-gas calculations; Section S2: Detailed emission-factor conversions; Section S3: Gravimetric ash-content calculation; Section S4: Detailed LCA, SEC and carbon-intensity calculations; Section S5: Detailed equal-energy economic calculations; Section S6: Detailed pellet production cost model.

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Abbreviations

The following abbreviations are used in this manuscript:

TCW	Textile Cotton Waste
TWS	Textile Wastewater Sludge
LCA	Life-Cycle Assessment
TEA	Techno-Economic Analysis
GHG	Greenhouse Gas
GCV	Gross Calorific Value
SEQS	Sindh Environmental Quality Standards
XRF	X-ray Fluorescence
U.S EPA	United States Environmental Protection Agency
EU	European Union

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