

**ADVANCING SUSTAINABLE TEXTILE DYEING SLUDGE MANAGEMENT: A
COMPREHENSIVE REVIEW OF CO-PYROLYSIS AS AN INNOVATIVE THERMAL TREATMENT
FOR CIRCULAR ECONOMY INTEGRATION AND ENVIRONMENTAL IMPACT MITIGATION**

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Abstract

This literature review critically discusses sustainable management techniques for textile dyeing sludge (TDS), a chemically toxic waste generated in huge quantities by the textile industry, leading to extensive environmental damage by chemical pollution, heavy metal toxicity, and excessive water and carbon release. The primary objective is to estimate the prospects of pyrolysis and co-pyrolysis as advanced, sustainable treatment methods for TDS out of available conventional methods, as part of the broader framework of circular economy strategies. Through a systemic approach, the study combines peer-reviewed research, and industry data to analyze and contrast biological, conventional thermal, and pyrolysis-based treatment technologies. Key findings indicate that pyrolysis and co-pyrolysis successfully reduce sludge volume, stabilize toxic components, and convert waste into useful commodities such as biochar, syngas, and bio-oil, optimizing resource recovery and waste valorization. Compared to biological processes, pyrolysis has enhanced contaminant immobilization and lowers environmental impact in various analyses. Co-pyrolysis, simultaneous thermal treatment of TDS with some other biomass or waste streams, achieves optimal energy recovery efficiency and lower emissions, enhancing circular economic ideas through closure of material loops and industrial symbiosis. The review has recognized pyrolysis as an economically and environmentally sustainable method for treating textile sludge, the co-pyrolysis contributes more to this with enhanced waste valorization and efficiency. These technologies are critical for guiding the textile industry towards green, circular production processes with less ecological harm while promoting economic resilience.

Keywords: Circular Economy, Co-Pyrolysis, Environmental Impact, Textile Dyeing Sludge (TDS), Pyrolysis

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Introduction

The textile industry is one of the major contributors to the world economic development in terms of employment availability and industrial growth. However, it is also a huge source of environmental concerns, especially in its carbon and water footprint (Konwar & Boruah, 2020). The lifecycle of textile products, from raw material extraction to disposal, emits greenhouse gases encompassing the carbon footprint (J. Zhang et al., 2020). Concurrently, the water footprint identifies freshwater utilized in textile production, including direct consumption and indirect uses like cotton cultivation and processing of raw materials.

Typically, a textile mill consumes ~1.6 million litres of water per day to produce about 8,000 kilograms of fabric. The industry employs enormous quantities of chemicals, with almost 8,000 variations such as metals, solvents, surfactants, and dyes (Bhatia et al., 2017; Khandare & Govindwar, 2015). Dyeing and finishing operations contribute 17% to 20% of industrial water pollution due to discharge of around 72 toxic chemicals, 30 of which are resistant to traditional wastewater treatments (Holkar et al., 2016). The extensive use of synthetic dyes, favoured for stability and economy, aggravates water pollution with high solubility, leading to highly contaminated effluents that pose threats to aquatic environments by inhibiting sunlight penetration and aquatic organisms.

In response to these environmental concerns, the textile industry is increasingly exploring circular economic principles. This approach emphasizes minimizing waste and maximizing the reuse and recycling of materials to establish a closed-loop system. However, the industry's rapid growth has led to increased generation of textile dyeing sludge (TDS), a byproduct of wastewater treatment. Although treatment methods have advanced with biological and chemical treatments, TDS remains a persistent byproduct. For instance, an industry consuming 50 m³ of water per hour can produce between 1 to 10 tons of sludge daily on a wet basis (Gomes et al., 2024). In countries like Sri Lanka, wastewater treatment plants predominantly utilize chemical treatments, resulting in significant sludge production with surplus biomass, chemicals, and refractory content. This makes it necessary to ensure intensive treatment before disposal into the environment.

Unfortunately, the information about the amount of TDS generation rates is not available in Sri Lanka or even globally. Despite that, the impact of textile sludge generation cannot neglect because it is multifaceted, affecting environmental, social, and economic dimensions. Environmentally, improper disposal or mismanagement of contaminated TDS severely contaminates soil and water sources, harming aquatic life and degrading freshwater quality due to containing toxic substances like heavy metals, dyes, and persistent organic compounds (Shirvanimoghaddam et al., 2020). Socially, communities near these facilities may face health risks from exposure to pollutants in sludge, and even workers may encounter occupational hazards related to sludge handling and disposal. In economic perspective, managing and treating TDS is costly, with environmental remediation liabilities. Inadequate sludge handling can also damage the reputation and market competitiveness of textile businesses.

Most of the hazardous waste, including 100% of sludge generated at the end of wastewater treatment plants in Sri Lanka are disposed through co-processing in cement kilns due to the lack of adequate hazardous waste treatment technologies (CEA, 2009). This method processes 95% of the hazardous waste, totalling 6847.4 tons per year, while the remaining waste accumulates due to limited treatment options (Adelizar et al., 2020; CEA, 2009). Still the concern about this problem is that industries must spent millions of rupees on this method being the only available validate disposal methodology.

As the textile industry expands on a global scale, addressing the social, environmental, and economic impacts of textile sludge production become increasingly vital. Specially in Sri Lankan textile industry a proper and sustainable layout has not develop to manage this generating TDS. The present review article attempts to address prevailing practice worldwide and in Sri Lanka for the treatment of textile sludge, considering their strengths and weaknesses. Through presenting detailed information on prevailing practices, the objective is to assess the most sustainable thermochemical approach in treating textile sludge. The review is on textile sludge complexities, including its genesis, composition, and the necessity of practicing sustainable management systems to prevent extreme environmental risks. Through the analysis of environmentally friendly processes and embracing circular economic concepts, the aim is to set out a direction for reducing the environmental footprint of the industry while enhancing consumer power.

Methodology

This study was conducted as a desk-based systematic literature review aimed at evaluating existing disposal methods for textile dyeing sludge (TDS) and identifying co-pyrolysis as a superior sustainable thermal treatment option for Sri Lanka. The methodology involved collecting, analysing, and synthesizing scholarly research and

technical reports to assess the environmental, technical, and economic aspects of various TDS treatment strategies as shown in Fig. 1.

The characterizations of the TDS in the identified papers were summarized get an idea about the nature of the sludge type. Findings were categorized based on disposal method and visualized through comparative tables and figures for clarity.

To organize the references and ensure proper citation, Mendeley reference management software was used. Graphical trends and thematic maps were created using Microsoft Excel and PowerPoint, where applicable, to present data patterns and identify research gaps.

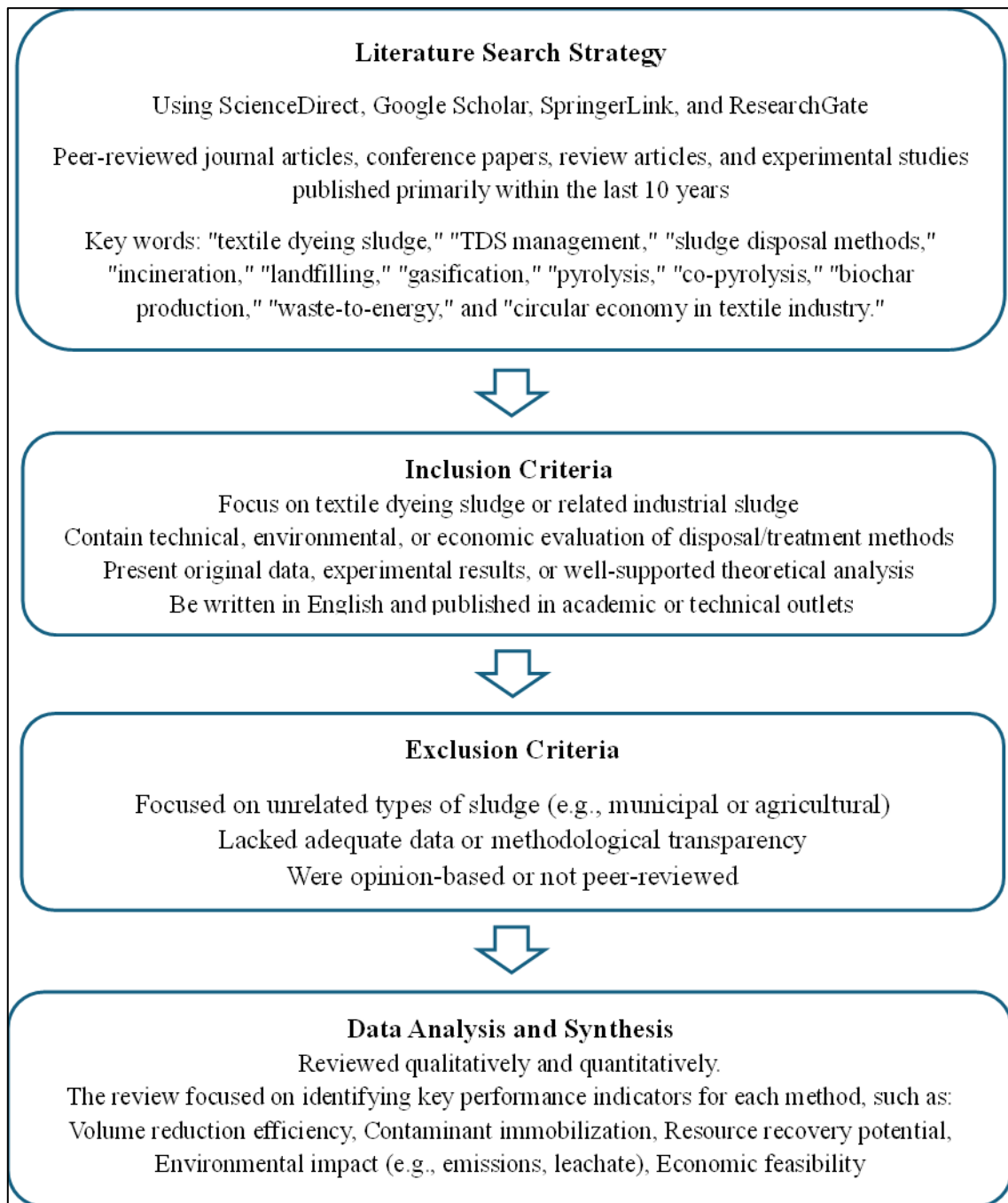


Figure 01: Flow Diagram of Methodology follow for the Literature Survey

Results and Discussion

Sludge Characterization:

Sludge obtained from effluent treatment plants consists of a cluster of organic and inorganic complexes. Furthermore, in textile sludge high concentrations of heavy metals such as Fe, Cu, Cd, Zn, and Cr are contained due to the dyes and chemicals that are used during the different wet processing stages. Most of the time the final

sludge from a textile plant is obtained as a combination of sludge from the primary sedimentation tank and the activated sludge from the oxidation tank. In such cases, the final sludge could have some microbes due to the microbial population coming from the activated sludge of the oxidation tank (Konwar & Boruah, 2020). Due to the high quantity of organics, inorganics, and biological residuals in textile sludge, it is considered an environmental pollutant. TDS management techniques such as open dumping led to soil, surface water, and groundwater contamination while being a threat to the aquatic environment, public health, livestock, wildlife, fish, and the whole biodiversity. Therefore, it is important to characterize the TDS and find an effective and sustainable sludge management technique (Konwar & Boruah, 2020; J. Zhang et al., 2020).

Physical and Chemical properties and variations

The TDS sample colour depends on the Effluent Treatment Plant (ETP) methods and chemicals. In most cases, the colour of the TDS is dark greenish, brown, or black. Similarly, the appearance can be watered fine solids or agglomerated fine solids (L. Wang et al., 2013). For sun-dried sludge, the appearance can be changed into hard agglomerated solids. The physicochemical properties of the characterized sludge in Table 1 show that wet TDS obtained from the wastewater treatment plant is acidic with a pH in the range of 4.5 – 5 for some studies. However, textile sludge obtained from India, Ethiopia, and China reported higher pH values in a range of 7.05 – 9.13. The sludge sample which has a high organic fraction shows total volatile solids percentage values in a range of 31.85-49.15 %. These variations of physiochemical properties can happen due to the dyes and chemicals used in the textile industries, methods, and dosage used in the ETP (Bhatia et al., 2017).

Table 01: Characterization of Textile Dyeing Sludge Generated in Different Wastewater Treatment Plants

| Reference | (X. Zhang et al., 2021) | (Wang et al., 2019) | (Liu et al., 2018) | (Xie et al., 2018) | (H. Zhang et al., 2017) | (Rao et al., 2019) | (Tapsoba et al., 2020) | (Arwa et al., 2018) | (Beshah et al., 2021) | (Badasubramanian et al., 2006) |
|-----------------------------|-------------------------|---------------------|--------------------|--------------------|-------------------------|--------------------|------------------------|---------------------|-----------------------|--------------------------------|
| Country | China | China | China | China | China | China | China | Tanzania | Bangladesh | Ethiopia |
| Sludge Type | Textile | Textile | Textile | Textile | Textile | Textile | Textile | Textile | Textile | Textile |
| pH | 7.05 | 7.28 | - | - | - | 7.31 | 9.00 | - | 7.44 | 9.13 |
| Moisture content | wt% | - | - | 11.70 | 1.37 | 39.18 | - | 80.00 | 21.40 | 28.72 |
| Volatile Matter | wt% | - | - | - | - | 23.66 | - | - | - | - |
| Total volatile solids | wt% | 49.15 | - | 23.90 | 44.71 | 36.53 | - | - | - | 31.85 |
| Total organic carbon | wt% | - | - | - | - | - | - | - | 20.70 | - |
| Ash content | wt% | - | 51.21 | 59.38 | 36.04 | 60.75 | 56.98 | - | 12.50 | 43.30 |
| Fixed Carbon content | wt% | - | - | 16.72 | 7.55 | 1.35 | 19.36 | - | - | - |
| Net Calorific value (LHV) | MJ/kg | - | - | 9.02 | 9.87 | 5.99 | 9.51 | - | 17.90 | 4.65 |
| Gross calorific value (HHV) | MJ/kg | - | - | - | - | - | - | - | - | - |
| Cu | mg/kg | 103.14 | 262.36 | 426.30 | 2900.00 | 302.80 | 286.01 | 42.16 | 58.00 | 30.00 |
| Cr | mg/kg | 116.72 | 251.16 | 482.29 | 39800.00 | 159.89 | 383.93 | 4.15 | 10.00 | 27.00 |
| Cd | mg/kg | - | 0.66 | - | - | 0.80 | - | 56.90 | 5.60 | 0.26 |
| Zn | mg/kg | 348.97 | 8930.15 | 2924.56 | 21500.00 | 1313.31 | 2101.07 | 111.42 | 131.00 | 272.00 |
| Ni | mg/kg | - | 183.95 | 71.20 | 7800.00 | 65.72 | 71.20 | 48.43 | 32.00 | 11.00 |
| Pb | mg/kg | - | - | 989.55 | - | 93.08 | 606.07 | 31.59 | 12.00 | 10.00 |
| Hg | mg/kg | - | - | - | - | 0.72 | - | 0.68 | - | 0.40 |
| Mn | mg/kg | 196.32 | 1601.20 | - | - | - | - | - | - | - |
| As | mg/kg | - | - | 16.30 | - | 90.96 | 49.04 | - | - | 5.00 |
| Co | mg/kg | - | - | - | - | - | - | - | - | 3.30 |
| Fe | mg/kg | - | - | - | 60100.00 | - | - | - | - | 75208.33 |
| Al | mg/kg | - | - | - | 601200.00 | - | - | 76.00 | - | - |

Furthermore, the ash content in the TDS samples varies notably, with China displaying the highest percentage at 59.38%, indicating varying levels of inorganic components. Fixed carbon content, a crucial indicator of potential energy yield, shows considerable disparities across regions, with values ranging from 1.38% in China to 19.36% in Ethiopia. These findings underscore the heterogeneity of TDS composition, influenced by regional factors such as industrial practices, environmental conditions, and waste management strategies. Understanding these variations is essential for devising effective management and utilization approaches for TDS in different geographical contexts.

Environmental Impact of the Conventional Methods of TDS Disposal.

Open dumping, landfilling, agricultural application, composting, and ocean dumping can be identified as available conventional methods for TDS disposal which pose significant environmental challenges and sustainability concerns. Open dumping is an unregulated deposit method of waste in exposed areas, leading to severe land degradation (Khandare & Govindwar, 2015). As a concern of this, toxic contaminants such as heavy metals, dyes, and hazardous chemicals leach to the soil and reduce fertility making it unsuitable for agriculture and posing risks

to aquatic ecosystems and compromising drinking water quality. Additionally, harmful gas emissions and persistent odors contribute to air pollution, creating health risks for nearby populations.

Landfilling is a more regulated method but continues to pose substantial environmental risks. Rainwater percolating through waste materials forms leachate which carries toxic substances into soil and groundwater systems, leading to long-term environmental degradation. Further this consumes valuable land resources and fails to effectively reduce TDS volume or ensure waste harmlessness (Karthik & Rathinamoorthy, 2015). Even engineered sanitary landfills face challenges managing TDS due to its complex composition of toxic chemicals and heavy metals. Environmental impacts include air, water, and soil pollution through uncontrolled production of gases such as methane and carbon dioxide, contributing to global warming. Approximately 17 million tons of textile waste ended up in landfills in 2018, representing 5.8% of total municipal solid waste generation making this an immense problem (U.S. Environmental Protection Agency, 2024).

The utilization of TDS for agricultural purposes, including soil amendment and fertilizer applications, presents complex environmental challenges. While this approach can provide nutrient enrichment for crops, it raises concerns about contaminant accumulation in soil and subsequent transfer to food crops, directly impacting food safety and quality (Tang, 2023). Land farming involves aerobic treatment of biodegradable organic matter in the upper soil layer, where improper planning and management can cause contamination of water sources, food supplies, and soil. In developing countries, agricultural applications have emerged as significant bulk utilization areas for TDS, but the presence of heavy metals and other pollutants can lead to soil contamination and adversely affect crop growth.

Composting of TDS faces challenges due to the persistence of synthetic fibers and chemical contaminants that can affect compost quality and safety. Research demonstrates mixed results, with direct composting showing negative effects on certain plant species while producing positive results for others, indicating variability in plant responses (A. Guha et al., 2015). Heavy metal analysis of TDSs reveals concentrations that can be detrimental to soil and plant health without adequate management. Biogas technology presents opportunities for energy recovery from TDS but faces hurdles due to anticipated toxicity, lower pH levels, and low carbon-to-nitrogen ratios, which impede anaerobic digestion efficiency (A. K. Guha et al., 2015).

Ocean dumping of TDS, now widely condemned and restricted in many nations, creates severe negative effects on marine environments. The TDS contains pathogens, harmful organic compounds, and metals that settle on ocean floors, modifying benthic communities and leading to the death of sensitive species. Bioaccumulation of metals and toxic compounds in the trophic chain ultimately reaches humans through consumption of contaminated fish and shellfish. Additionally, nutrients in TDS promote plankton growth and increased dissolved oxygen consumption, disrupting marine ecological balance (Karthik & Rathinamoorthy, 2015).

The conventional methods of TDS disposal demonstrate widespread environmental impacts across air, water, and soil systems, with contamination effects extending to human health through food and water sources. With textiles taking up to 200+ years to decompose in landfills and only 14.7% of textile waste being recycled in the United States, there is an urgent need for sustainable alternatives (RoadRunner, 2021). The complex composition of TDSs, containing heavy metals and toxic chemicals, necessitates advanced treatment technologies and circular economy strategies to minimize environmental footprint and promote sustainable textile industry practices.

Environmental Impacts of Thermal Treatment Technologies of TDS Disposal.

Thermal treatment methods, such as incineration, gasification, and torrefaction present alternative strategies for managing TDS with high-temperature processing as shown in Fig 2. The main aims of these methods are to reduce waste volume and recover energy from the TDS. However, they could also pose environmental challenges that must be carefully considered.

In incineration, TDS burnt at high temperatures (>850°C) to reduce its volume and eliminate toxic bacteria and harmful pathogens (Xie et al., 2018). The main products of this combustion process are flue gas, slag, and fly ash (Wu et al., 2024). The organic matter in the TDS is oxidized and decomposed into carbon dioxide and water, releasing heat energy that can be recovered during incineration (Xie et al., 2018).

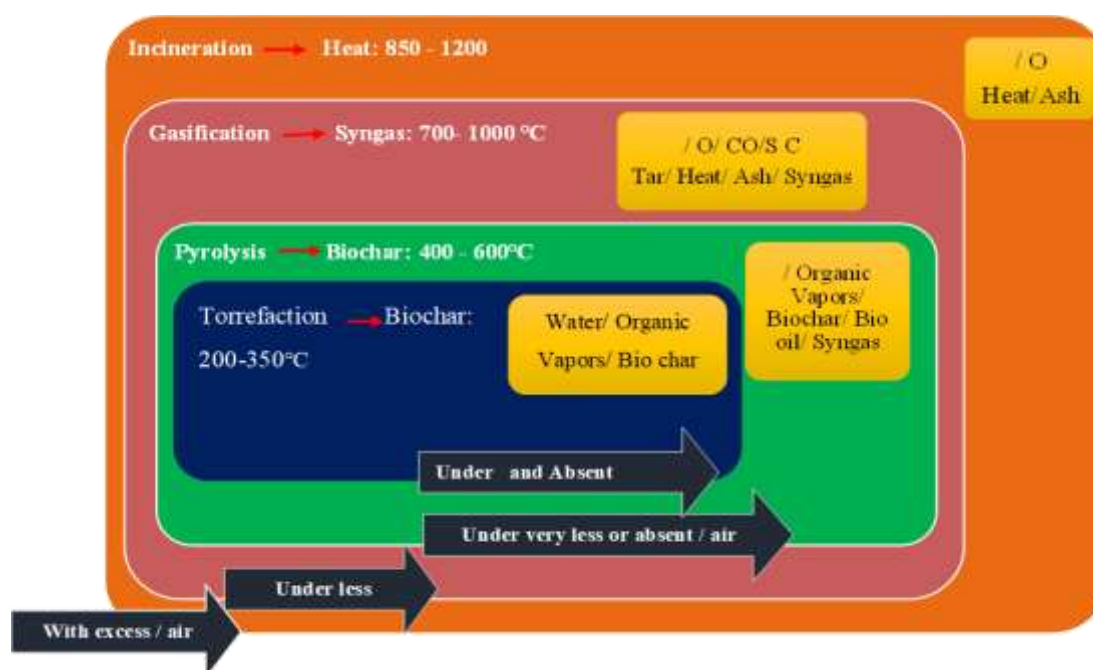


Figure 2 - Schematic representation of torrefaction, pyrolysis, gasification and incineration stages

Despite its benefits, gaseous emissions and heavy metals produced as pollutants during incineration (Raju & Vasanth Kumar, 2025). These emissions, such as dioxins and particulate matter, can negatively impact air quality and pose risks to human health (Raju & Vasanth Kumar, 2025). Therefore, balancing the energy recovery potential of incineration with its environmental emissions is crucial.

Gasification is an emerging technology that converts waste materials, including TDS, into valuable products like hydrogen and carbon monoxide in an efficient and eco-friendly manner (M. Wang et al., 2024). Unlike incineration, gasification involves the partial combustion of waste at high temperatures (700-1200 °C) with a controlled oxygen supply (M. Wang et al., 2024). This products of this method can be used for secondary combustion or further processed into energy products like syngas or biogas (Zhao et al., 2023). M. Wang et al., (2019) has studied, CO₂ thermal plasma gasification can have a carbon conversion efficiency of up to 99.9%.

One significant advantage of gasification is its potential to produce biogas, a renewable energy source for power generation or fuel but low evaporation yields, and the removal of final slag can be challenging (G. Zhang et al., 2024). Additionally, gasification may involve higher transportation costs and more complex gas purification processes compared to other waste-to-energy technologies (M. Wang et al., 2019). The residue from gasification may also leach heavy metals and organic pollutants, representing a significant environmental concern (Zhao et al., 2023).

Torrefaction is a mild pyrolysis process at 200–300°C under inert conditions to upgrade sludge by improving its fixed carbon content and reducing moisture. This enhances sludge quality for subsequent energy conversion. As previous methodologies, heavy metals in sludge can cause environmental pollution during thermochemical processes, posing negative impacts (Manatura et al., 2022).

The discussed methods contribute to greenhouse gas emissions, along with particulate matter and hazardous ash production, contribute to global warming and environmental degradation (Wu et al., 2024; Zhao et al., 2023). Therefore, sustainable waste management approaches are needed to mitigate these environmental impacts.

The complexity of emission control systems required for thermal treatment facilities increases capital and operational costs while posing technical challenges for effective pollutant management. The variability in waste composition also affects combustion characteristics and emission profiles, necessitating adaptive management approaches for different waste streams. Innovative and sustainable waste management solutions are crucial for mitigating environmental impacts and enhancing resource recovery opportunities.

Pyrolysis

Pyrolysis is a thermochemical decomposition process which involves breaking down organic materials in an oxygen-free environment, under high temperatures, typically between 300°C and 700°C (X. Wang et al., 2019). This process results in three primary products: solid biochar, liquid bio-oil, and gaseous syngas. The produced biochar can be used as a soil amendment, adsorbent, or in construction materials. Bio-oil, due to its rich organic content, can be refined for use as a renewable liquid fuel or as a chemical feedstock. The syngas output, primarily consisting of hydrogen, methane, carbon monoxide, and carbon dioxide, make it useful as a fuel for energy generation or further chemical synthesis (X. Wang et al., 2019).

The ability to convert hazardous waste into valuable resources while producing fewer emissions than traditional combustion methods make pyrolysis an environmentally friendly process. The immobilization of heavy metals in biochar and the reduced formation of secondary pollutants can identify as key environmental advantages (Y. Liu, Ran, Rizwana, et al., 2018). Over recent years, the application of pyrolysis has expanded to waste treatment, including municipal solid waste, industrial sludge such as TDS, and biomass residues. In the case of TDS, which contains high inorganic content and low calorific value, mono-pyrolysis yields lower-quality products (X. Wang et al., 2019). Co-pyrolysis, the simultaneous pyrolysis of TDS with other carbon-rich feedstocks like biomass or waste oils, significantly improves the process outcome (Hu et al., 2021).

Table 2 discuss about how studies have pyrolyzed TDS with different materials, in different conditions, and how they have affected to the final products.

Table 02: Literature Review Analysis of Pyrolysis Methodology used to Treat Textile Dyeing Sludge

| Table | Materials and Source | Pyrolysis Method and Conditions | Effect of Pyrolysis into Results |
|---------------------------------------|---|---|---|
| (H. Zhang et al., 2017) | Textile dyeing sludge, CaO, Fe | Microwave -assisted auger pyrolysis (MWAP), 450-750°C, N ₂ and Ar gas atmosphere | Increased gas yield, with decreased char and oil yields at higher temperatures. CaO and Fe increased hydrogen (H ₂) yield and improved sulfur retention in char. |
| (Y. Liu, Ran, Rizwana, et al., 2018) | Textile dyeing sludge | Fluidized bed pyrolysis and MWAP, 450-850°C | MWAP yielded more char and liquid, while FBP produced more gases. Heavy metals were retained in char. |
| (Y. Liu, Ran, Siddiqui, et al., 2018) | Textile Dyeing Sludge from a wastewater treatment plant in China | Fluidized bed pyrolysis, 450°C-850°C, Nitrogen used as the fluidizing gas | The surface morphology of char improved at higher temperatures. CO, CH ₄ , and H ₂ yields increased with temperature. |
| (X. Wang et al., 2019) | Textile dyeing sludge | Quartz tube pyrolysis, 300-700°C, Argon atmosphere | Higher temperatures reduced bioavailable heavy metals and leaching risk. Biochar became more stable and had lower environmental risks at temperatures above 400°C. |
| (Ran et al., 2019) | Textile Dyeing Sludge from a wastewater treatment plant in southern China | Fluidized bed pyrolysis reactor, 450°C-850°C, nitrogen as fluidizing gas | Co-pyrolysis with CaO, kaolin, and Ca-bentonite improved gas and condensate yields. Heavy metals were stabilized in char. Higher temperatures resulted in more gas yield and less char. |
| (Ding et al., 2021) | Textile dyeing sludge, medical plastics (PP, PE) | Co-pyrolysis with varying TDS: plastic ratios, 400-550°C | Co-pyrolysis increased hydrocarbon yield and reduced CO ₂ emissions. Optimal blend ratio was 1:9 TDS-to-plastic. Biochar showed improved porosity and stability. |
| (J. Liu et al., 2021) | Textile dyeing sludge with | Pyrolysis at 800°C in He, incineration at 600-950°C | FeCl ₃ increased burn rate but also emissions, while CaO reduced NO _x |

| | | | |
|------------------------|--|---|--|
| | FeCl ₃ and CaO treatments | | and SO ₂ emissions by forming stable compounds. |
| (Hu et al., 2021) | Textile dyeing sludge, bamboo residues | Co-pyrolysis with TDS:BR ratios, TGA-FTIR analysis, XPS | Strong synergistic effects, especially at 1:1 ratio. Co-pyrolysis improved biochar stability, reduced NO _x precursors, and increased gas yields. |
| (Scheibe et al., 2022) | Textile sludge (Brazilian) | Pyrolysis at 500°C for 70 minutes under reduced pressure | Oily phase showed antibacterial properties and had a high heating value, making it a potential alternative fuel and biocide. |
| (Feng et al., 2022) | Paper mill sludge, Textile Dyeing Sludge, Duckweed, Waste Tires | Fixed-bed pyrolysis, 400-700°C, N ₂ atmosphere | Co-pyrolysis enhanced gas and liquid product yield. Reduced pollutants and residue content. |
| (Wahab et al., 2023) | Textile and leather wastewater sludge, γ-zeolite, Al ₂ O ₃ catalysts | Fixed-bed pyrolysis at 500°C in N ₂ atmosphere | Catalysts reduced activation energy. Al ₂ O ₃ increased oil yield slightly; γ-zeolite improved oil quality, reducing oxygenated compounds and promoting deacidification. |
| (Hossain et al., 2024) | Textile sludge, tannery fleshing waste | Co-hydrous pyrolysis at 300°C under 20 MPa pressure for 60 minutes | Highest biocrude yield was obtained from 1:1 TS:TFW ratio with good energy recovery and fuel properties. |
| (Ding et al., 2024) | Textile dyeing sludge mixed with polyethylene, polypropylene | Co-combustion/pyrolysis in air, CO ₂ /O ₂ , and N ₂ atmosphere at 300-1000°C | MPs increased VOC emissions and enhanced the volatilization of metals at higher temperatures. CaCO ₃ in PP reduced metal residues in ash. |
| (Zhou et al., 2024) | Textile dyeing sludge, Furfural residue | Microwave-assisted auger pyrolysis (MWAP), 450-750°C, N ₂ and Ar gas | Higher energy and exergy efficiency for furfural residue. Lower environmental impact. Gas yield increased with temperature, and char yield decreased. |

According to the literature presented in the Table 2 the effectiveness of pyrolysis process is highly reliant on the reactor design and operating conditions employed. Reactor designs vary in terms of heating mode, capacity to process, and selectivity to products, with each being tailored to specific applications and target products. Likewise, temperature, residence time, rate of heating, and inert atmosphere determine the yield and purity of pyrolysis product, as well as stabilization of toxic content. It requires an in-depth understanding of these variables for the sake of developing effective systems that maximize product value and minimize environmental risks.

A) Use of Different Reactors

Various reactor systems are designed for pyrolysis according to the material or waste type using and desired product required to gain. Fixed-bed reactors are commonly designed for slow pyrolysis and due to that they offer high biochar yields compared to other products and are cost-effective (Feng et al., 2022). Due to their uniform heating characteristics these reactors are particularly suited for biochar-focused applications and simpler operational requirements make it ideal for batch operations (Wahab et al., 2023).

Fluidized bed reactors (FBP) are designed with a bed of inert material fluidized by nitrogen or inert gas which helps to provide excellent heat transfer and uniform reaction conditions making it ideal for high gas yields and faster processing (Y. Liu, Ran, Siddiqui, et al., 2018). FBPs have proven particularly efficient in handling fine particles and produce a consistent product stream (Y. Liu, Ran, Siddiqui, et al., 2018).

Microwave-assisted auger pyrolysis (MWAP) uses internal electromagnetic heating and continuously operating with a moving screw to process materials (H. Zhang et al., 2017). MWAP achieves rapid and uniform heating and higher yielding of bio-oil while reducing energy consumption (Zhou et al., 2024). MWAP systems are designed with better control over product distribution, especially in low-energy settings.

Hydrous pyrolysis is a natural geologic process operated under water and pressure, converting waste like raw material into biocrude with improved calorific values (Hossain et al., 2024). Although this technically is more complex compared to other discussed reactors, this approach has shown considerable promise in generating energy-rich oil fractions with minimal residue.

The selected reactor type decides the final product type and the quality making the designers responsible for the choose the best and appropriate one.

Impact on Operating Conditions

The efficiency and outcomes of products from pyrolysis of TDS are significantly influenced by operational parameters such as temperature, residence time, and the use of inert sweeping gases. These factors determine the distribution and quality of the resulting products, biochar, bio-oil, and syngas and as well as the stabilization of hazardous elements like heavy metals.

Temperature is the main critical factor in pyrolysis. Lower temperatures (300–500°C) preserve more of the carbon structure and produce biochar, which is beneficial for applications like soil amendment (Ding et al., 2021; Hossain et al., 2024; X. Wang et al., 2019). In higher temperatures (600–850°C) complex hydrocarbons breakdown, increasing the yields of syngas components such as hydrogen, carbon monoxide, and methane (Feng et al., 2022; J. Liu et al., 2021; X. Wang et al., 2019; Zhou et al., 2024). For instance, studies have shown that increasing the pyrolysis temperature from 400°C to 600°C can decrease biochar yield from 37.14% to 30.6%, while increasing syngas yield from 38.92% to 56.64% (H. Zhang et al., 2017). Additionally, higher temperatures result in biochar with increased alkalinity due to the concentration of inorganic minerals like calcium and potassium.

The use of inert sweeping gases, such as nitrogen or argon, is essential to create an oxygen-free environment, preventing combustion during pyrolysis. These gases facilitate controlled thermal decomposition, enhancing the production of valuable gases and aiding in the stabilization of heavy metals within the biochar matrix. Argon helps with heavy metal stabilization by suppressing their volatilization (Zhou et al., 2024).

Residence time means the duration the feedstock remains in the reactor, also plays a pivotal role. When the duration is shorter, favor the production of liquid and gaseous products by limiting secondary reactions, whereas longer residence times promote greater carbonization, resulting in higher biochar yields (H. Zhang et al., 2017). However, excessively long residence times can damage the biochar's pore structure, reducing its surface area and effectiveness (Y. Liu, Ran, Siddiqui, et al., 2018).

The pyrolysis efficiency can significantly improve by incorporating catalysts, such as calcium oxide (CaO) and iron powder (Fe) (H. Zhang et al., 2017). These catalysts help the breakdown of hydrocarbons, increasing hydrogen yields and reducing carbon dioxide emissions. They also support stabilizing heavy metals by forming stable mineral compounds, thereby reducing their volatility and leachability, which enhances the environmental safety of the resulting biochar (J. Liu et al., 2021).

Overall, optimizing pyrolysis conditions, temperature, residence time, heating rate, and the use of inert gases and catalysts is crucial for maximizing the efficiency of TDS treatment. Such optimization not only improves the yields and quality of pyrolysis products but also enhances environmental safety by stabilizing hazardous elements.

Co-Pyrolysis

Co-pyrolysis, the simultaneous thermal decomposition of multiple waste materials in an inert atmosphere, enhances the valorisation of TDS by improving product yields, energy recovery, and environmental outcomes.

Mixing TDS with carbonaceous materials like plastics or biomass generates synergistic effects that optimize the pyrolysis process (Ding et al., 2021, 2024; Feng et al., 2022; Hu et al., 2021). Co-pyrolysis of TDS with polypropylene and polyethylene, for instance, increases hydrocarbon production and energy recovery (Ding et al., 2024). Incorporation of medical plastics lowers energy activation, which favors faster decomposition and higher gas yields. A 1:9 ratio of TDS to plastics realizes optimum gas outputs, especially methane and light hydrocarbons, and lowers CO₂ emissions (Ding et al., 2021). Similarly, 1:1 TDS-to-bamboo ratio also optimizes gas yields of CO₂, CO, and CH₄ and minimizes nitrogen oxide emissions by suppressing the formation of nitrogen-containing compounds (Hu et al., 2021).

Co-pyrolysis also improves the quality of biochar. The addition of materials like calcium oxide (CaO) or kaolin to the process stabilizes heavy metals like zinc, lead, and nickel in the biochar, rendering the biochar more environmentally suitable for use in applications like soil amendments (Feng et al., 2022; Ran et al., 2019; H.

Zhang et al., 2017). Besides, co-pyrolysis of TDS with high-calorific value materials, e.g., waste tires, raises bio-oil yield and quality via enhanced production of aromatic and olefinic compounds, rendering the bio-oil more suitable for fuel applications (Feng et al., 2022).

Importantly, co-pyrolysis reduces toxic emissions. Co-pyrolysis of TDS and medical plastics, for example, was reported to reduce CO₂ emission and enhance energy recovery (Ding et al., 2021). These synergistic effects not only optimize the pyrolysis process but also enable more environmentally sound waste management systems.

It can be identified that compared to pyrolysis, co-pyrolysis performs better due to the advantages of getting from the synergetic effect of each other. Overall, co-pyrolysis offers a promising approach to waste management by improving product yields, enhancing quality, and reducing environmental impacts. By carefully selecting feedstock combinations and optimizing process conditions, co-pyrolysis can contribute to more sustainable and efficient waste-to-energy solutions.

Pyrolysis or Co-pyrolysis Products and their Applications

The primary products of pyrolysis bio-oil, biochar, and syngas have significant industrial and environmental applications, but their quality and properties depend heavily on the feedstock and operating conditions.

Bio-oil is a heavy, dark liquid consisting of a large group of organic compounds including hydrocarbons, fatty acids, phenols, and oxygenates. At moderate to high temperature pyrolysis, it is produced. Bio-oil has a high energy density (19-33 MJ/kg) and can be upgraded to chemical feedstocks or liquid fuels (Scheibe et al., 2022). Its composition is different with pyrolysis conditions, e.g., co-pyrolysis of textile dyeing sludge with waste tires enriched its content of valuable hydrocarbons, broadening its application as a fuel (Feng et al., 2022).

Biochar is the solid residue carbon-rich left behind after pyrolysis. It is valued for its porosity, high carbon content, and large surface area, and is thus found to be effective as an adsorbent for the extraction of pollutants from soil and water. Through research (H. Zhang et al., 2017), the use of iron powder and CaO powder resulted in char with enhanced surface area (up to 91.9 m²/g), ideal for pollutant adsorption. Heavy metal stability in the biochar is a crucial environmental parameter, and the introduction of chemicals like CaO under pyrolysis conditions can reduce the mobility of harmful metals (J. Liu et al., 2021).

Syngas (Non-Condensable Gases): Pyrolysis gases, which consist of hydrogen, carbon monoxide, methane, and minor amounts of other gases, are extremely versatile as a source of renewable energy (Zhou et al., 2024). More heat during pyrolysis reactions enhances the production of gases, while catalysts like CaO can increase the quality of gases by reducing CO₂ and hydrogen yields (H. Zhang et al., 2017).

Discussion of findings from previous studies

Textile dyeing sludge (TDS) treatment remains a worthwhile environmental and operational challenge in developed and developing countries alike. This review compared a broad range of TDS disposal methods conventional, thermal, and novel thermochemical with the aim of identifying the most sustainable, economically viable, and environmentally friendly solution.

The conventional methods such as landfilling, open dumping, composting, and agricultural use are still predominant since they are simple and cheap. Nevertheless, these activities pose long-term environmental threats in the form of groundwater contamination, soil degradation, heavy metal bioaccumulation, and greenhouse gas emissions. Particularly in Sri Lanka, cement kiln co-processing is one of such examples of an industry having to depend significantly on already existing although second-best solutions due to limited alternatives.

Thermal treatments like gasification and incineration are characterized by improved volume reduction and pathogen destruction but are tainted with their high capital and operating costs, difficulty in emission control, and poor value recovery through the end products. The paper points out that incineration, despite its efficiency in waste reduction and sterilization, is largely offset by the emission of toxic gases and ash residues. Gasification holds much promise, particularly for energy recovery, but it is made unviable by the requirement of rigorous waste pre-treatment and gas cleaning systems.

Pyrolysis, however, has been a very promising alternative since it can transform TDS into biochar, bio-oil, and syngas each of which has possible applications in agriculture, energy, and environmental remediation. Above all, co-pyrolysis, when TDS is combined with high-carbon feedstocks such as plastics, biomass, or waste oils, increases the value and efficiency of the process even more. Synergistic pyrolysis improves the quality of biochar, immobilizes heavy metals, boosts gas yields, and reduces toxic emissions. It is best suited for treating low-calorific and inorganic-rich feedstocks such as TDS.

Interestingly, the review noted a glaring research gap in implementation in developing countries like Sri Lanka. Despite a plethora of supportive remarks in experimental data, the lack of local policy frameworks, technology transfer establishments, and stakeholder sensitization hinders the application of co-pyrolysis. This gap reflects the urgent need for inter-disciplinary collaboration among policymakers, researchers, and industry leaders to translate laboratory-level success into tangible, industrial-level solutions.

Conclusions and Recommendations.

The textile sector accounts for a very substantial contribution to global environmental problems, specifically in the form of enormous carbon and water footprints and production of toxic TDS. Traditional disposal techniques involving landfilling and incineration entailing the risk of pollution and health concerns. Among recently developed technologies, one widely recognized for its potential for TDS management is pyrolysis, which is a thermal decomposition process conducted in conditions of restricted or no oxygen supply. Pyrolysis transforms TDS into biochar, bio-oil, and syngas and has numerous environmental benefits. The process lowers the Polycyclic Aromatic Hydrocarbons content, and thus the resulting biochar is safer to apply for enriching soils. In addition, high-energy density bio-oil and syngas byproducts are potential alternative fuels that can be used for energy recovery and fossil fuel reduction. Co-pyrolysis is better than mono-pyrolysis because synergetic effect is enhanced in the product quality. Integration of pyrolysis into a circular economy system enhances the efficiency of resources in generating useful products from waste from the context of sustainable development. For the optimal application of pyrolysis for local TDS management, it is recommended to: (1) have supportive policies and legislation in place to encourage the application of pyrolysis technology; (2) facilitate research and development activities to improve pyrolysis conditions for different textile sludges; (3) identify other feedstocks that can be blended with TDS and co-pyrolysis to yield improved quality end-products; and (4) carry out additional research to investigate long-term environmental and economic impacts of pyrolysis-based TDS management. By embracing pyrolysis within a circular economy model, the textile dyeing industry can minimize its impact on the environment significantly while tapping hidden resources.

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