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Waste Management and Recycling of Industrial By-Products

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Abstract

This study explores a systematic approach to waste management by identifying re-use and recycling options through a two-stage methodology. Initially, a questionnaire was employed to collect data on waste types, quantities, and current or planned recycling activities. The second stage involved categorizing wastes into eight classes based on their characteristics, performing a keyword database search using six commercially available databases, and identifying potential process options and treatment technologies. The database search, refined through keyword clustering, reduced 191,721 entries to 112,179, focusing on commercially viable practices. Various waste types, including chemicals, plastics, metals, and sludges, were analyzed for their re-use and recycling potential. The study identified several treatment technologies, such as chemical recovery, thermal recycling, and material reprocessing, with cost estimates categorized into three ranges. Additionally, specific re-use options for select waste streams, such as recovery of metals, mercury, and organic compounds, were evaluated. The findings highlight the critical importance of segregation at source to maximize recovery value and demonstrate the feasibility of innovative waste management strategies tailored to market demands and cost considerations.

Keywords*:* Waste Management, Industrial By-products, Recycling

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Introduction

Industrial waste management and recycling have become critical focal points in the quest for sustainability and environmental protection. With the increase in global industrial activities, the amount of waste generated has surged, leading to severe environmental and economic consequences. Industrial by-products are typically categorized into several types—chemicals, solids, plastics, metals, oils, sludges, and other materials—which, if not managed properly, can cause pollution, resource depletion, and inefficiency in manufacturing processes. The rise in industrial waste has led to greater emphasis on sustainable waste management practices that focus on reducing, reusing, and recycling waste rather than relying on traditional disposal methods like landfilling and incineration. Recycling industrial by-products not only helps in minimizing environmental harm but also creates economic opportunities by recovering valuable materials and reducing the need for raw resources. Economic and Environmental Benefits of Waste Recycling Recycling industrial by-products is crucial for both environmental sustainability and economic growth. It reduces the need for raw materials, which are costly and energy-intensive to extract, lowering production costs and waste disposal expenses. This leads to greater operational efficiency, profitability, and competitiveness. Recycling also helps conserve natural resources, reduces energy consumption, and lowers greenhouse gas emissions, contributing to environmental protection. Additionally, it reduces landfill waste and minimizes the environmental risks of landfilling and incineration. Advances in recycling technologies, such as chemical recycling (pyrolysis, gasification, depolymerization), allow for the recycling of complex materials like plastics, further enhancing the efficiency of recycling systems and supporting more sustainable industrial practices.

Advanced Recycling Technologies- Recycling technologies have undergone significant advancements over the past few decades, driven by innovations in material science, chemistry, and engineering. The traditional methods of recycling, such as mechanical recycling, which involve shredding and remolding materials, have been widely used for years but are limited in their ability to handle complex waste streams. These limitations have necessitated the development of more sophisticated techniques to address the increasing variety and volume of industrial waste, particularly as materials grow more diverse and the need for recycling becomes more urgent.

Chemical Recycling- Chemical recycling is a promising advancement that uses chemical reactions to break down materials into their components, allowing them to be repurposed into new products. Unlike mechanical recycling, it can process difficult-to-recycle materials like mixed plastics or those contaminated with oils, paints, or food residues. Key methods include pyrolysis, which decomposes organic materials at high temperatures to produce oils, gases, and chemicals; depolymerization, which breaks down polymers for reuse; and solvolysis, which uses solvents or heat to break down materials for reprocessing. These techniques reduce waste and help produce valuable raw materials.

Pyrolysis and Gasification

Pyrolysis is a process where waste materials like plastics and rubber are heated to high temperatures (350°C to 900°C) in an oxygen-free environment, breaking them down into oils, gases, and solid residues. These outputs can be refined into fuels, used for electricity generation, or applied in industrial uses like tire reinforcement. Gasification is similar but involves partial combustion in limited oxygen to produce syngas, which can generate electricity or be converted into synthetic fuels. Both processes are key components of waste-to-energy systems, reducing landfill volumes and environmental pollution.

Economic Considerations of Recycling Technologies

Advanced recycling technologies, while offering environmental and economic benefits, involve high initial investment for research, infrastructure, and equipment. Establishing chemical recycling plants can be costly, and these systems require specialized skills. However, the long-term advantages often outweigh the initial costs, such as reduced waste disposal fees and the need for raw materials. Recycling also lowers dependency on energy-intensive virgin materials, saving costs and reducing environmental impact, particularly in metals like aluminum, steel, and copper, which require less energy when recycled.

Review of Literature

Ajay Kumar (2023): Industrial waste in India, particularly from factories, poses environmental challenges. Recycling waste materials, such as tires, glass, and slag, for highway construction can reduce demand for traditional materials while addressing disposal issues. Using these materials not only benefits the environment but also cuts production costs.

Nithya (2021): Waste is generated through material wear and tear and can harm the environment when not managed properly. Many waste materials, however, contain organic compounds, nutrients, and energy resources that can be recovered and reused through bio-based waste management techniques, fostering sustainability and a green economy.

Ebikapade Amasuomo (2016): The definition of waste is subjective, as what one person considers waste may be viewed as a resource by another. The paper emphasizes the need for clear definitions of waste to support effective regulation and management practices. Jaana Sorvari (2014): Industrial by-products like metallurgical slags and ashes from energy production have potential for reuse, especially in construction and agriculture. The technical and environmental properties of these materials, along with processing methods, determine their suitability for recycling.

Brigitta Tóth (2013): The study examined by-products such as grinding sludge and sewage sludge compost for their potential use in plant nutrition. The findings suggest these materials, rich in essential nutrients, can be used to address nutrient deficiencies in agriculture, though careful application monitoring is necessary.

Objectives of the Study

1. To evaluate the effectiveness of advanced recycling technologies in reducing industrial waste.
2. To analyze the economic and environmental benefits of recycling industrial by-products.

Hypothesis

H1: There is a significant reduction in industrial waste through the use of advanced recycling technologies.

H2: There is a significant contribution of recycling industrial by-products to economic and environmental benefits, such as cost savings and resource conservation.

Research Methodology

The research methodology consisted of a two-stage approach. Stage 1 utilized a questionnaire to collect data on waste types, quantities, and current or planned re-use and recycling activities. Stage 2 involved four steps: classifying wastes into eight categories based on characteristics, conducting a keyword database search using six commercially available databases, identifying potential process options, and evaluating treatment technologies and costs. Keyword clustering refined database search results, reducing entries from 191,721 to 112,179, ensuring a focus on commercially viable re-use and recycling practices.

Data Analysis

Table: 1 Classification of Waste Types and Quantities

Waste Type	Quantity
Chemicals	18
Solids, sludges, and slurries	34
Plastics	49
Paper and board	7
Oils and solvents	12
Metals	28
Containers	12
Miscellaneous	10

The table presents a classification of waste types and their corresponding quantities based on a survey. Among the waste categories, plastics account for the largest proportion with 49 units, followed by solids, sludges, and slurries at 34. Chemicals and metals are also significant, with 18 and 28 units, respectively. Oils and solvents contribute 12 units, while containers also account for 12. Paper and board constitute the smallest category, with only 7 units. The inclusion of a "Miscellaneous" category, comprising 10 units, reflects the need to account for a diverse range of waste materials that don't fit neatly into other classifications. This classification scheme highlights the variety and volume of industrial waste types and emphasizes the importance of targeted recycling strategies.

Data Base Search

The next step was to undertake a data-base search, based on key-word clusters. The search used six databases and a strategy of key-words. The databases were all commercially available covering either waste or materials topics and are shown below in Table 2:

Table 2: Databases Used

Database	Topics covered
Waste info	waste management
Enviroline	environmental and resources
Ceab	chemicals and their processing
Metadex	metals and alloys
Rapra	rubbers and plastics
Pira	paper, packaging, printing and nonwovens

The key-words covered the materials of interest and were combined with ‘end-use’ application words, such as ‘re-use/recycling/recovery/utilisation of waste’, to form a master set of references. To further refine the search, the key-word ‘commercial’ was added, defining a field of search that concentrated upon waste materials re- used/recycled commercially. This was found to be an essential step, due to the very large number of references identified by the data-base search. To illustrate the practical importance of the need to combine key search words into clusters to specify a well-defined area of interest, consider the following results in Table 2 from one such search.

Table 3: Example of Database Entries

Search word/cluster	No. of entries
Re-use	6,282
Recovery	59,045
Recover	72,311
Recycling	54,083
Total	191,721
1-4 as a cluster	112,179

The reduction in entries noted above, arising from the search, reduced from 191,721 for the individual word entries, to 112,179 by the removal of duplicate entries. The proper use of word clusters is an essential part of data base searches, to minimise both the number of duplicate entries and to save on unnecessary costs when downloading the output.

Process Options

The references obtained from the database search were enhanced by other information sources (Refs 2-8), to produce a listing of materials and potential process options for their beneficial use. The main options are summarised in Table 3, together with an example of the type of waste material involved.

Table 4: Potential Process Options

Option	Waste material	
Direct recovery or re-use	acid/alkaline solutions with metals or dissolved organics acid solution pickle liquor acid/alkaline sludges with metals heavy metals	volatile metals concentrated organic liquids organic salts and sludges
Raw materials for secondary use	non-contaminated acid solutions acid solutions with heavy metals (except Cr pickle liquor) acid solutions with dissolved/emulsified organics alkaline solutions with metals/organics	volatile metals concentrated organic liquids organic salts
Energy recovery	emulsified organics alkaline solutions with organics concentrated organic liquids	tar and residues organic sludges
Pollution control uses	non-contaminated acid solutions acid solutions/pickle liquor alkaline solutions with metals	
Substances with a low potential for recovery	acid /alkaline sludges not containing metals cyanide solutions cleaning solutions salt solutions alkali metals	asbestos dilute aqueous solutions of solvents etc. strong oxidising agents explosives biological wastes

Of the various process options available the first three involve treatment technologies to recover the material as either a recyclate, or via its intrinsic thermal value. For each of the waste types identified in Table 3, a range of recovery routes are usually available. Summary details only are presented in this paper but full technical descriptions are contained in references 2, 3 and 6.

Table 4 illustrates potential treatment technologies available for a range of different waste types.

Chemicals	Basic recovery routes: in-house use of by-products/wastes as feedstock for other chemicals recovery of organic solvents used as process separation media thermal value for process heating recycling of off-specification product directly to the process or for less critical applications
Solids, Sludges & Slurries	chemical precipitation ion exchange electrolytic recovery evaporation solvent extraction flotation adsorption reverse osmosis electro-dialysis
Plastics	Reprocessed or recycled: primary recycling by sorting, cleaning, granulation, blending & compounding and extrusion/moulding chemical recycling by methanolysis/hydrolysis/pyrolysis thermal recycling by incineration
Paper & Board	pulp substitute “bulk” or packaging pulp
Oils	refining, removal of soluble/insoluble contaminants by distillation and acid/caustic/solvent/clay treatments reprocessing, removal of insoluble contaminants by a combination of heating/settling/filtering/dehydration/centrifuging and blending reclamation, separation of solids and water by a combination of heating/settling/filtering/dehydration/centrifuging and blending to a constant viscosity
Solvents	decantation sedimentation centrifugation filtration flash distillation neutralisation and chemical addition
Metals	ferrous, by basic oxygen or electric furnace steelmaking non-ferrous (primarily aluminium) by smelting

The above Table is a simplistic (and limited) listing of technologies but they do represent the key processing options for each of the waste classification groups. The identification of potential technologies involves consideration of a number of factors, apart from simply the processing technology. Thus separation/segregation, collection, transport and marketing are all factors to be taken into consideration, in addition to the actual processing technology. It is considered by the author that the key factor in the above list is separation at source and segregation, whereby the maximum gain in any subsequent processing is obtained at minimal cost. The value of waste is reduced considerably, sometimes to a negative value, by poor waste management practices at source, where the simple action of physically keeping wastes products/materials in appropriate, separate groups can enhance their value, either for subsequent re-use or recycling activities.

Treatment Technology Costs

Having identified potential process options, the next stage of the project was to provide some indication of the likely order of cost of the technologies identified. This was achieved by using a combination of published data, supplemented by telephone discussions with UK companies active in the technology of interest. Companies were generally very helpful on both technical and economic matters and their co-operation was a key factor in the successful completion of the project. An order of cost basis is all that could reasonably be expected in a project of this nature and three cost ranges were developed;

- •X= low cost i.e. <£100,000
- •XX= medium cost i.e. £100,000 <£1,000,000
- •XXX= high cost, i.e.>£1,000,000

The costs refer to capital costs for a specific capacity of plant, a capacity considered appropriate for the arisings of that waste stream in the SMA. For example, a regeneration plant for waste sulphuric acid being produced at 5000t/m, is estimated as costing of the order.>£1,000,000 (i.e. XXX); the estimated cost of a plant to recycle contaminated lubricants and fuel oil is <£100.000-£1,000,000 (i.e. XX); and a plant to recycle PVC waste from wire coating operations by granulating and re-using in the same process is estimated as costing <£100,000 (i.e. X). A feasibility study would be needed to more accurately determine the costs for a specific application or project.

Table 5: Wastes and Order of Cost for Potential Recycling Treatments

Waste	Quantity (te/month)	Source Of Waste	Cost
Chemicals			
waste sulphuric acid	5,000	toluene isocyanate	XX
acrylonitrile solution (46%)	450	acrylonitrile	XX
methanol liquor	100	hexamethyltetramine	XX
orthotoluene diamine	30	toluene isocyanate	XX
waste acids	200	sulphonated oils	XXX
Solids, sludges & slurries			
Fe-Si-Mn slag	10,000	ferro alloys	XX
cathode blocks	120	alumina	XX
deactivated alumina	60	polyethylene	XX
carbon ash	2	activated carbon	X
calcium oxide slurry	6	galvanised tubing	X
Ni/Mo catalyst	0.6	white refined oils	XXX
Plastics			
polyester resins/gels	30	polyester paints/solvents	XX
nitrile polymers	0.4	acrylonitrile	X/XX
waste polypropylene	5	industrial textiles	X
rubber pieces	0.4	rubber products	X
HDPE dust	0.3	HDPE	X
waste PVC	0.3	PVC coated wire	X
Paper & Board			
paper drums	300	additives for various items	X
paper/board	12	chemicals, packaging etc.	X
paper sacks	1	PVC products	X
Oils & Solvents			
contaminated lubricants contaminated fuel oil transformer oil	25 0.5 0.1	maintenance iron foundry products maintenance	XX XX XX
Metals			
pellet dust	600	rolled steel products	X/XX
iron shavings	180	manufacturing, foundries etc.	X/XX
scrap iron	27	fabrication	X/XX
scrap aluminium bars	300	reduction of alumina	X/XX
Containers			
metal	100 units	PE, dyes, PVC coatings, acetylene	X
plastic	150 units	galvanised tubing, textiles, toluene isocyanate	X
Miscellaneous			
distillation wastes greases laboratory glassware filter bags	1 0.3 0.2 0.6	polyester resins iron foundry products ethylbenzene, polystyrene acrylic fibres	XX XX XX XX

Waste Re-use Options

In addition to recycling options for wastes as materials, some specific uses for particular waste streams were identified (Table 6). These end-use options were obtained from the database search references and supplementary sources and refer specifically to the situation in the SMA.

Table 6: Specific Re-Use Options for Selected Wastes

Waste	Process/Use
Calcium carbonate	recovery of metals from Cu process sludges
Fe/Al scrap	used to condition effluent streams for the recovery of metals by precipitation recovery of Cu & Ag from solutions by reduction with Fe/Al scrap
Sulphuric acid	recovery of As from anodic Cu slimes recovery of Cd by reacting Cd bearing aqueous wastes with ferrous sulphate & sulphuric acid, leaching at 800 C, mixing residue with soda & calcining at c.6000 C
Mercury contaminated salts	heating wastes in a retort to recover mercury
Hydrochloric acid	treating sludges containing phenyl/amyl mercury compounds to recover mercury
Phthalic anhydride	residues used as feedstock for producing maleic anhydride
Caustic soda	processing waste caustic from petroleum refining to recover sodium sulphide and cresylic acid added to waste acrylonitrile solutions with alcohol & hypochlorite for sewer disposal
Activated carbon	recovery of cresols/phenols from waste water recovery of fatty acids, organic acids/bases, oils, fats & plasticers from filter media, such as clays & carbon, by solvent extraction recovery of non-ferrous metals from primary copper smelter discard by reducing with carbon and calcium carbonate and recovering metals as Cu-As-Bi-Sn alloy
Scrap rubber tyres	Whole tyres for reef building, erosion control, highway barriers etc. spit/punched tyres for floor mats, shoe treads, gaskets/seals, insulators & bumpers

These examples serve to illustrate that a range of options exist for the re-use of waste materials, in addition to the more traditional recycling techniques of oil/solvent recovery, paper recycling etc. The selection of appropriate treatment technologies will therefore be largely determined by the availability of markets for the wastes.

Discussion

The study demonstrates a comprehensive approach to identifying and evaluating waste re-use and recycling opportunities, emphasizing both the classification and potential processing of various waste types. Initially, waste materials were categorized into eight classes based on their characteristics, including chemicals, solids, plastics, metals, oils, and miscellaneous items. This classification allowed a pragmatic understanding of diverse waste streams and ensured an efficient framework for data analysis. The methodology included a two-stage process: data collection through surveys and a detailed database search using keyword clusters to streamline results. The refinement of entries from 191,721 to 112,179 highlighted the importance of focused clustering for cost-effective and precise data retrieval. Subsequent analysis identified multiple treatment technologies for waste management. For example, chemicals can undergo recovery or thermal treatment, plastics can be recycled mechanically or chemically, and metals can be processed via smelting or reuse in production cycles. Innovative methods such as utilizing scrap rubber tyres for infrastructure and activated carbon for recovering valuable substances illustrate the potential of waste-to-resource strategies. The economic feasibility of these processes was analyzed, with treatment costs ranging from low (<£100,000) to high (>£1,000,000), depending on the complexity and scale of operations. Such cost evaluations provide insight into the economic viability of implementing recycling technologies at various scales. Furthermore, the study identified specific re-use options for particular waste streams, demonstrating that market demand significantly influences the choice of treatment technologies. For instance, sulphuric acid and mercury-contaminated salts were found suitable for metal recovery processes, while caustic soda and phthalic anhydride residues could serve as feedstock in chemical production. This aligns with the broader objective of minimizing waste disposal and maximizing resource recovery. Overall, the study underscores the critical role of systematic waste classification, targeted database searches, and the strategic selection of processing technologies in promoting sustainable waste management practices. The findings emphasize the necessity of source segregation, market alignment, and cost-effective solutions to enhance the re-use and recycling of waste materials in industrial and commercial contexts.

Conclusion

This study presents a comprehensive framework for identifying and evaluating re-use and recycling options for diverse waste streams, emphasizing both environmental sustainability and economic feasibility. By categorizing wastes into eight classes and employing a keyword-based search strategy, it highlights the significance of tailored approaches and clustering techniques for optimizing waste management practices. The findings underscore the importance of source segregation and innovative recycling options, such as using calcium carbonate in metal recovery and repurposing scrap rubber tires for construction, to enhance resource utilization. Moreover, cost analysis reveals the economic viability of recycling technologies, offering a roadmap for sustainable waste management investments. Overall, the study underscores the need to align waste treatment strategies with technological capabilities and market dynamics to support a sustainable circular economy.

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