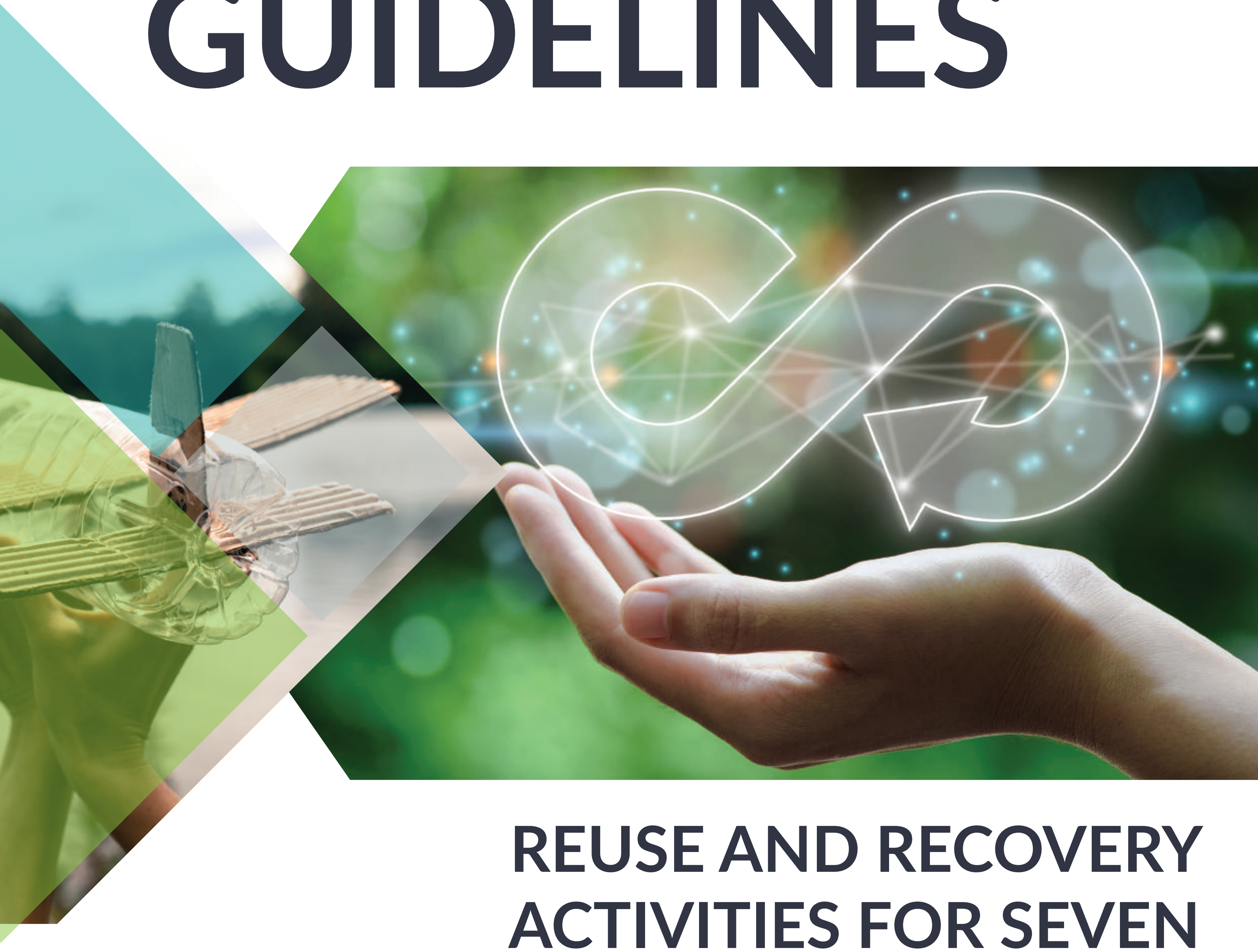
TECHNICAL GUIDELINES



REUSE AND RECOVERY ACTIVITIES FOR SEVEN SCHEDULED WASTE

DEPARTMENT OF ENVIRONMENT MALAYSIA

Department of Environment, Malaysia

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PREFACE

In recent years, the issue of waste management has emerged as one of the most pressing environmental challenges faced by nations worldwide. Malaysia, with its rapidly growing economy and population, is no exception. As the country advances towards sustainable development, it is imperative that we address the environmental impact of industrial activities, particularly concerning scheduled wastes.

Scheduled wastes pose significant risks to both human health and the environment if not managed properly. Recognizing this, Malaysia has taken proactive steps to establish comprehensive regulations and guidelines aimed at minimizing the negative effects associated with these wastes. These Guidelines represent a pivotal component of this broader effort.

This document serves as a crucial resource for industries, regulators, and environmental practitioners involved in the management and treatment of scheduled wastes. It provides a detailed framework for the safe and effective reuse and recovery of these materials, highlighting best practices, technical requirements, and compliance standards. By adhering to these guidelines, stakeholders can ensure that waste management practices not only meet regulatory expectations but also contribute to the overarching goal of environmental sustainability.

The guidelines outlined herein are the result of extensive research, expert consultation, and practical experience. They reflect the latest advancements in technology and methodology, tailored to the specific context of Malaysia's scheduled waste management landscape. Furthermore, they underscore the importance of integrating environmental considerations into industrial processes, thereby promoting a circular economy that minimizes waste and maximizes resource efficiency.

As Malaysia continues its journey towards a greener future, the successful implementation of these guidelines will be instrumental in mitigating environmental impacts and fostering sustainable practices. We encourage all stakeholders to engage with these guidelines diligently and to contribute to the collective effort of enhancing waste management practices in our nation.

In guidance with these guidelines, it is anticipated that the development of scheduled waste reuse and recovery activities shall result in positive economic and social benefits while ensuring that the sustainable development can be achieved, and the environment is preserved.

DATO' WAN ABDUL LATIFF BIN WAN JAFFAR
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LIST OF ABBREVIATIONS

4R	Reduce, Reuse, Recycle, Recover
AAB	Alkali Activated Cement Binders
ACA	Accelerated Capital Allowance
ADMI	American Dye Manufacturers Institute
APCS	Air Pollution Control Systems
ASTM	American Society for Testing and Materials
BAT	Best Available Techniques
BOD	Biochemical Oxygen Demand
BOD_5	Biochemical Oxygen Demand measured in water sample during 5 days of incubation
BS	British Standards
BS EN	British Standards incorporating a European Standard
CCPT	Climate Change and Principle-based Taxonomy
CIDB	Malaysian Construction Industry Development Board
CIS	Construction Industry Standard
COD	Chemical Oxygen Demand
DAC	Dialdehyde Cellulose
DADS	Diallyl Disulphide
DOE	Department of Environment
EC	European Commission
EGC	Electroconductive Geopolymer Composite
EIA	Environmental Impact Assessment
EPA	Environmental Protection Agency
EQA 1974	Environmental Quality Act 1974
ERS	Electronic Reporting System
ESG	Environmental, Social, and Governance

ESM	Environmentally Sound Management
ESP	Electrostatic Precipitator
eSWIS	Electronic Scheduled Waste Information System
FGD	Flue Gas Desulphurisation
FGDG	Flue Gas Desulphurisation Gypsum
GRI	Global Reporting Initiative
GSPP	GS Paperboard and Packaging Sdn. Bhd.
i-ESG	National Industry Environmental, Social and Governance
IEC	International Electrotechnical Commission
ITA	Investment Tax Allowance
JSM	Department of Standards Malaysia
KASA	*Kementerian Alam Sekitar dan Air*
KKR	Ministry of Works
KPKT	Ministry of Housing and Local Government
LCA	Life-Cycle Assessment
LiB	Lithium-Ion Batteries
Li-ion	Lithium-Ion
LOI	Loss-on-Ignition
LWA	Lightweight Aggregates
MAFI	Ministry of Agriculture and Food Industries
MGTC	Malaysian Green Technology and Climate Change Corporation
MIDA	Malaysian Investment Development Authority
MITI	Ministry of International Trade and Industry
MS	Malaysian Standard
MS EN	Malaysian Standard incorporating a European Standard
NASA	National Aeronautics and Space Administration
NCEC	National Circular Economy Council
NGOs	Non-governmental Organizations
NMVOC	Non-Methane Volatile Organic Compound
NOx	Nitrogen Oxides
NRECC	Ministry of Natural Resources, Environment and Climate Change
OECD	Organization for Economic Co-operation and Development
PASCA	*Pelan Strategik Pengurusan Buangan Terjadual 2015*
PCDD	Polychlorinated dibenzodioxins
PCDF	Polychlorinated dibenzofurans
PETRONAS	National Petroleum Limited

PG	Phosphogypsum
PVC	Polyvinyl Chloride
RG	Red Gypsum
RPM	Revolution per Minute
RRM	Renewable Resource Material
SCM	Supplementary Cementitious Material
Si-Mn	Silico-Manganese
SIRIM	Standard and Industrial Research Institute of Malaysia
SMEs	Small Medium Enterprises
SSF	Simultaneous Saccharification and Fermentation
SWCorp	Solid Waste and Public Cleansing Management Corporation
TCFD	Task Force on Climate-related Financial Disclosure
TRLs	Technology Readiness Levels
VBIAF	Value-based Intermediation Assessment Framework
UK	United Kingdom
USA	United States of America
VOCs	Volatile Organic Compounds
WAC	Waste Acceptance Criteria
XLPE	Crosslinked Polyethylene

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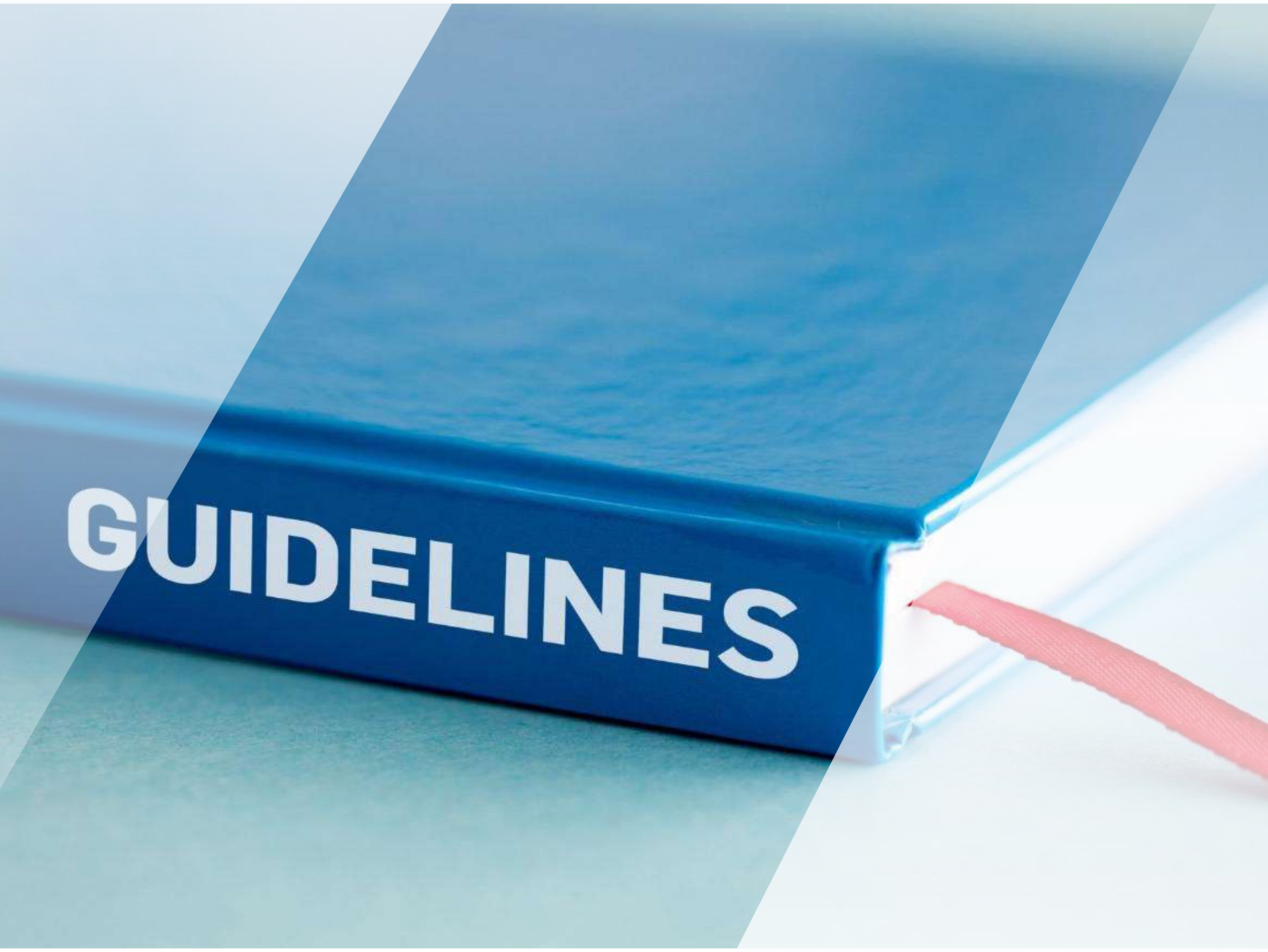
1 INTRODUCTION



CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

In the realm of scheduled waste management in Malaysia, there is a notable shift from the traditional “cradle-to-grave” approach towards a more sustainable “cradle-to-cradle” model. The “cradle-to-cradle” is a design concept introduced by McDonough and Braungart (2010) which aims to develop products and systems that mimic nature's processes by being restorative and regenerative by design.

It is based on the principles of material health, material reutilization, renewable energy, water stewardship and social fairness. It advocates for a practical shift towards designing products and systems that can cycle indefinitely, whether as technical or biological nutrients, without creating waste or pollution.

This transition strongly encourages industries to actively reduce the generation of scheduled waste by embracing on-site reuse and recovery practices, thus decreasing reliance on secure landfills. This pivotal shift finds its roots in the principles of the circular economy, which are firmly grounded in the pursuit of resource efficiency and the minimization of waste generation.

The traditional linear economy, which follows a “take-make-consume-dispose” model, is no longer sustainable from an environmental perspective. In contrast, the circular economy aims to reduce environmental impact and decrease dependence on natural resources.

Key concepts within the circular economy other than Cradle-to-Cradle includes Performance Economy, Biomimicry, Industrial Ecology, Natural Capitalism, and the Blue Economy Approach. The primary goal is to promote sustainability and material circularity by minimizing waste and resource input through eco-design, recycling, and responsible product use, incorporating life-cycle assessment (LCA) principles.

The definition of key terms related to circular economy framework for scheduled waste management is defined in **Figure 1-1**. Apart from the usual reduce, reuse, recycle and recovery in the context of waste management, scheduled wastes also require treatment operation to ensure environmentally sound management.

Figure 1-1: Working Definitions of Terms Related to the Circular Economy Framework for Scheduled Waste Management[1,2,3,4]

Reduce

- Measures to be taken before a substance, material or product has become waste, that reduce:
- The quantity of waste including through the re-use of products or the extension of life span of products.
- The adverse impacts of generated waste on the environment and human health.
- The content of hazardous substances in materials and products.

Reuse

- Operations by which product, object and substance are used again for the same or alternative purposes for which it was conceived that promotes resource efficiency without the necessity of pre-processing.

Recycle

- Operations by which waste materials are reprocessed into products, materials and substances, whether for the original or other purposes. It does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling.
- In these Guidelines, this term will be included under the "Recovery" umbrella.

Recovery

- Operations where waste is serving a useful purpose by replacing other material which would otherwise have been used to fulfil a perticular function, or waste being prepared to fulfil that function, in the plant or in the wider economy. This includes material recovery/reclamation, energy recovery, and and reprocessing into materials that are to be used as fuels or other means to generate energy.
- However, in the context of waste reporting, incineration with and/or without energy recovery is considered as disposal operation, which aligns to the practice and principles of Basel Convention and sustainability reporting standards (such as Global Reporting Initiative).

Treatment

- Processing operations that change the biological or physico-chemical properties of waste, including interim operations which prepare waste prior to reuse, recovery or final disposal operations.

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1 European Union, *Directive 2018/851/EU of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste*.

2 Secretariat of the Basel Convention, *Basel Convention Glossary of Terms*, 2017, 13-21.

3 Secretariat of the Basel Convention, *Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal*, 2020, 54-55.

4 *Environmental Quality (Prescribed Premises) (Scheduled Wastes Treatment and Disposal Facilities) Order 1989*.

In Malaysia, various agencies, such as the Solid Waste and Public Cleansing Management Corporation (SWCorp), the Malaysian Construction Industry Development Board (CIDB) and the Malaysian Green Technology and Climate Change Corporation (MGTC), promote the circular economy through sustainable production and consumption. The Green Technology Master Plan Malaysia 2017-2030 encompasses energy, environment, economy, and social pillars.

Private companies like GS Paperboard & Packaging Sdn. Bhd. (GSPP), Petroliam Nasional Berhad (PETRONAS), Top Glove Corporation Berhad, Venator Asia Sdn. Bhd. and YTL Cement have demonstrated a proactive approach by successfully integrating and implementing circular economy principles into their operational frameworks.

Scheduled wastes, categorized based on their hazardous characteristics, are managed under the Environmental Quality (Scheduled Wastes) Regulations 2005. Regulation 7 of the Environmental Quality (Scheduled Wastes) Regulations 2005 specifically permits off-site treatment or recovery, incentivizing the reuse of scheduled waste as raw materials. The Department of Environment (DOE) has also issued Guidelines for the Application of Special Management of Scheduled Wastes and Guidelines on Environmentally Sound Co-Processing of Scheduled Wastes in Cement Industry to further fortify these efforts.

To further this agenda, a feasibility study is underway in Malaysia, with a focus on managing high-volume wastes like gypsum waste (SW 205) and silico-manganese slag waste (SW 104). The study aims to enhance reusability, reduce environmental impact, and explore waste recovery and processing technologies which are described in the Guidelines, with hopes that it would ultimately lead to the creation of industrial clusters that align with the concept of Industrial Ecology. These collective efforts underscore DOE's dedication to sustainable development and environmental preservation.

1.2 OBJECTIVES OF THE GUIDELINES

The primary goal of the Guidelines is to serve as a comprehensive resource and reference point for industry players. It aims to provide clear and practical guidance on various reuse and recovery technologies applicable to specific scheduled wastes.

This document is intended to facilitate a deeper understanding of these technologies, their processes, the waste acceptance criteria, operating conditions, potential benefits, and limitations etc. It serves as a starting point for industry stakeholders who seek to explore, study, and potentially implement these solutions within their operations.

By offering insights into available reuse and recovery technologies, the Guidelines hopes to empower industry players to make informed decisions about which approaches align best with their needs and environmental goals. It encourages further studies and investigations into the practicality and suitability of these technologies within specific contexts.

Ultimately, the objective is to promote sustainable practices in scheduled waste management by offering industry players the knowledge required to contribute to environmental conservation and resource efficiency through the responsible management of scheduled wastes.

1.3 SCOPE OF THE GUIDELINES

The Guidelines focus on the reuse and recovery technologies for seven (7) selected types of scheduled wastes, corresponding to the following scheduled waste codes:

- SW 103 – Waste of Lithium-Ion (Li-Ion) Batteries
- SW 104 – Silico-Manganese (Si-Mn) Slag from Ferroalloy Industries
- SW 110 – Spent Insulated Copper Wires and Cables
- SW 202 – Spent Catalysts
- SW 204 – Sludge Containing Heavy Metals from Paper Mill
- SW 205 – Waste Gypsum from Chemical Industries
- SW 321 – Rubber or Latex Wastes

The scopes of the Guidelines are as follows:

- Outline all relevant information and documents, application forms and relevant checklists;
- Outline the appropriate method/technology/process for reuse and recovery of selected scheduled wastes based on the technology used in developed countries;
- Outline the specifications of the products produced from the reuse or recovery activities of the selected scheduled wastes;
- Outline Government policies and current legal requirements related to scheduled waste reuse and recovery activities; and
- Provide an overview of reuse and recovery activities of scheduled wastes in accordance with the circular economy concept.

1.4 STRUCTURE OF THE GUIDELINES

The structure of the Guidelines is as follows:

- **Chapter 1:** Introduction
- **Chapter 2:** Government Policies and Legal Requirements
- **Chapter 3:** Overview of Scheduled Waste Management in Malaysia
- **Chapter 4:** Reuse and Recovery Options of Selected Scheduled Wastes
- **Chapter 5:** Pollution Control Systems

1.5 USAGE GUIDE ON TECHNOLOGY SELECTION AND IMPLEMENTATION PROCESS

This Chapter provides a guide on the possible steps required in selecting and implementing technology solutions for efficient scheduled waste management and circular economy practices. Effective technology selection is essential for achieving sustainable scheduled waste management and resource recovery goals. The recommended stages in **Table 1-1** intends to assist stakeholders in making informed decisions and successfully integrating reuse and recovery technologies into their operations.

Table 1-1: Recommended Steps on Technology Selection and Implementation Process

Step		Description
STEP 1	Identifying Needs and Objectives	• Clearly define the organization's specific needs, goals, and objectives related to scheduled waste management and circular economy.
STEP 2	Waste Characterization	• Thoroughly characterize the scheduled waste(s) in question. • Understand its composition, physical properties, and any hazardous components, involving laboratory analysis and data gathering from various sources.
STEP 3	Assessment and Evaluation of Available Technologies	• Explore, assess and evaluate the available technologies that align with the identified needs, objectives, and waste characteristics. • Identify the potential reuse or recovery technology suitable for the specific scheduled waste. • Certain available technologies for the selected scheduled wastes are exemplified in **Chapter 4**.
STEP 4	Feasibility Study	• The purpose of a feasibility study is to assess the practicality and potential outcomes of the selected technology. • These studies should involve capital costs, operational expenses, location, resource availability, environmental impacts, and potential risks to assess the practicality and viability of the chosen technology or practice.
STEP 5	Pilot Testing	• Whenever feasible, conduct pilot-scale tests or trials of the selected technologies. • These tests help assess the real-world performance of each technology adopted to the local scheduled waste characteristics, identify any operational challenges, and fine-tune the process parameters.

Step		Description
STEP 6	Environmental Impact Assessment (where applicable)	• These assessments are essential to evaluate the potential environmental impacts and ensure compliance with regulatory requirements, namely the Environmental Quality Act 1974 (Act 127) (**Chapter 2.3.1**). • An EIA should be conducted prior to the deployment of any facility that is a prescribed activity as listed under the Environmental Quality (Prescribed Activities) (Environmental Impact Assessment) Order 2015 (**Chapter 2.3.1.8**).
STEP 7	Obtain All Necessary Permits and Approval	• Identify all licenses and approvals required for the proposed scheduled waste management activities. • These applications may include Written Permission and License (refer to **Chapter 2.3**) for prescribed premises and/or prescribed conveyances (where applicable); Written Notification and Written Declaration for pollution control systems. • Ensure that any additional approvals needed for constructing and using prescribed premises and conveyances are obtained from the relevant regulatory authorities.
STEP 8	Full-Scale Implementation	• Execute the full-scale implementation of the selected technology, closely monitoring its performance. • Ensure that chosen technology complies with local regulations and standards. • Continuously monitor the technology's performance and make necessary improvements for optimization.

1.6 DISCLAIMER

The technologies and related information presented in this document (in **Chapter 4**) are intended for reference and informational purposes only. They are provided to offer insights and guidance regarding the management of selected scheduled waste, available technologies, and details of related processes.

It is important to note that while this document offers a comprehensive overview, it may not cover the full spectrum of reuse applications or recovery technologies available worldwide. The field of scheduled waste management is dynamic and constantly evolving, with new innovations and practices emerging regularly.

Therefore, the absence of specific reuse applications or recovery technologies in this guidance document does not imply their nonexistence or lack of viability. Waste receivers and generators are encouraged to explore additional resources and consult experts in the field for the most up-to-date and diverse range of options suitable for their specific waste management requirements.

The information provided in this Chapter does not imply pre-approval by the Department of Environment (DOE), Malaysia, for immediate application. Rather, it serves as a foundational reference and should be complemented by laboratory analyses when considering the adoption or implementation of a particular approach. Parameters may vary based on factors such as the source of raw materials, production processes, and operating conditions.

1.6.1 Key Considerations

Feasibility Studies and Assessments: Waste receivers and generators considering the adoption or implementation of the technologies discussed herein are strongly advised to conduct comprehensive feasibility studies. These studies should encompass technical, financial, operational, and environmental aspects to assess the practicality and viability of the chosen technology or practice within their specific context.

Laboratory Analysis: The waste characteristics of the selected scheduled wastes outlined in **Chapter 4** are primarily sourced from secondary data, including research papers and articles. It is essential to recognize that the composition and concentration of scheduled wastes generated at individual sites may vary. Therefore, for precise and site-specific information, it is strongly recommended to conduct laboratory analyses on the scheduled waste in question. These analyses will provide a more accurate understanding of the waste's composition, ensuring that scheduled waste management strategies are tailored to the specific characteristics of the scheduled waste generated at each site.

Environmental Impact Assessments (EIA): Additionally, the critical importance of EIA should be recognized. These assessments are essential to evaluate the potential environmental consequences and ensure compliance with regulatory requirements, namely the Environmental Quality Act 1974 (Act 127). An EIA should be conducted prior to the deployment of any facility that is a prescribed activity as listed under the Environmental Quality (Prescribed Activities) (Environmental Impact Assessment) Order 2015.

Consultation and Expert Advice: Engaging with relevant experts, environmental consultants, regulatory authorities, and stakeholders should be conducted during the feasibility study and assessment phases. Expert advice can provide valuable insights into the specific challenges, risks, and opportunities associated with scheduled waste management and related activities.

Legal and Regulatory Compliance: Scheduled waste management is subject to legal and regulatory frameworks detailed in **Chapter 2**. Compliance with all relevant laws, regulations, and permits is mandatory.

1.6.2 Important Note

The information provided in this document is not a substitute for professional advice, regulatory compliance, or due diligence. The authors and publishers do not assume any liability for the consequences of using or implementing any technology or practice without proper feasibility studies, analysis, assessments, and compliance with relevant laws and regulations.

Users are strongly urged to exercise diligence, conduct comprehensive assessments, and seek expert guidance to ensure their scheduled waste management practices align with best practices, environmental protection, and legal requirements.

2

GOVERNMENT POLICIES AND LEGAL REQUIREMENTS

CHAPTER 2

GOVERNMENT POLICIES AND LEGAL REQUIREMENTS

2.1 INTRODUCTION

In the context of environmental conservation and sustainable development, the effective management of scheduled waste plays a central and indispensable role. Throughout the years, Malaysia has established a comprehensive regulatory framework to address the management of scheduled waste in order to strive towards a cleaner, safer, and more sustainable country.

Since the Sixth Malaysian Plan (1991–1995), the Government has reinforced regulations pertaining to scheduled wastes. Incentives were introduced for compliant companies, while penalties were also imposed on non-compliant industries. The initially “cradle-to-grave” principle for scheduled waste management has now slowly transitioned to the “cradle-to-cradle” concept, which is a crucial step for the nation to achieve circular economy.

This Chapter explores the existing Government policy and the legal framework underpinning scheduled waste management in Malaysia.

2.2 RELEVANT GOVERNMENT POLICIES AND PLANS

2.2.1 Twelfth Malaysian Plan, 2021-2025

The Twelfth Malaysian Plan (2021-2025) is a five-year agenda planned with the objective to achieve the Shared Prosperity Vision 2030, which encompasses three dimensions: economic empowerment, environmental sustainability, and social re-engineering (**Figure 2-1**).

Figure 2-1: Theme 3 (Advancing Sustainability) in the Twelfth Malaysian Plan (2021 – 2025)

2.2.2 Green Technology Master Plan Malaysia, 2017 – 2030

The Green Technology Master Plan Malaysia (2017-2030) was established with the objective to create a framework which facilitates the mainstreaming of green technology into the planned developments of Malaysia while encompassing the four pillars set in the National Green Technology Policy, i.e., energy, environment, economy and social.

Under the goal to achieve sustainable utilization of natural resources, waste management was identified as one of the target key sectors. One of the initiatives realized for waste management is strengthening the institutional framework. The Government has set up a National Committee of Sustainable Waste Management that shall work towards reduction of the seven (7) categories of waste (including scheduled waste) in Malaysia, through actions such as:

- Streamline the roles and responsibility of related agencies;
- Improve data collection comprehensiveness; and
- Assess feasibility and market creation for green technology growth within the waste management sector.

2.2.3 Environmental Sustainability in Malaysia, 2020 – 2030

The Environmental Sustainability in Malaysia (2020 – 2030) was established by The Ministry of Environment and Water of Malaysia [*Kementerian Alam Sekitar dan Air*

(KASA)][5]. The strategic plan is built upon four (4) thrusts: empowered governance, green growth, strategic collaboration, and social inclusiveness, which aims to set strategy and direction for the Ministry to enhance environmental sustainability from 2020 to 2030.

Some initiatives realized under the strategic plan which are related to waste management are:

- 50% increase in recycling rate for scheduled waste by 2030, compared to 17% recycling rate in 2020;
- Establish a total of five (5) waste to wealth facilities by 2030, compared to 2 facilities in 2020; and
- Increase total green investment to RM 100 billion in terms of Gross Domestic Product (GDP), as compared to RM 20 billion in terms of GDP in 2020.

2.2.4 Strategic Plan for the Management of Scheduled Waste, 2015

The Strategic Plan for the Management of Scheduled Waste [*Pelan Strategik Pengurusan Buangan Terjadual 2015* (PASCA)] by the Department of Environment (DOE) Malaysia aims to provide governance guidance to the enforcement agency and all other scheduled waste management stakeholders.

The objective of the strategic plan is to promote waste management that improves environmental sustainability and economic competitiveness, based on the principle of "cradle-to-cradle" and through strengthening of the 4R principle (reduce, reuse, recycle and recover).

Eight (8) key strategies were determined to achieve excellence in the management of scheduled waste and hazardous material:

- **Strategy 1:** Empowering national policies and legislation for scheduled waste management;
- **Strategy 2:** Strengthen enforcement of scheduled waste;
- **Strategy 3:** Environmental forensic science approach;
- **Strategy 4:** Improve the application of 4R principles and safe disposal methods;
- **Strategy 5:** Strengthen international cooperation;
- **Strategy 6:** Explore new options towards the direction of strengthened scheduled waste management;
- **Strategy 7:** Empower and cultivate human capital among enforcement officers and waste management stakeholders; and
- **Strategy 8:** Stakeholder engagement.

[5] Kementerian Alam Sekitar dan Air (KASA), *Environmental Sustainability in Malaysia (2020 – 2030).*

2.2.5 National Policy on Climate Change

The National Policy on Climate Change serves as a framework to ensure climate-resilient development to fulfil national aspirations for sustainability. This policy has three (3) core objectives:

- Mainstreaming climate change through wise management of resources and enhanced environmental conservation resulting in strengthened economic competitiveness and improved quality of life;
- Integration of responses into national policies, plans and programmes to strengthen the resilience of development from arising and potential impacts of climate change; and
- Strengthening of institutional and implementation capacity to better harness opportunities to reduce negative impacts of climate change.

To effectively address climate change, a series of key actions related within the realm of waste management are listed in the policy:

- Systematic review and harmonization of existing legislation, policies and plans;
- Identify and recommend pathways toward establishing a low-carbon economy;
- Incorporate measures for financial mobilization and technical assistance into waste management initiatives; and
- Integration across policies and programs.

2.2.6 Green Investment Incentives

Green investment incentives are allocated to promote the development of green services, including waste management in Malaysia. The Malaysian Investment Development Authority (MIDA) is an agency in charge of the promotion and coordination of industrial development under the Ministry of International Trade and Industry (MITI). The Green Technology Tax Incentive was first introduced in 2014 to incentivize the development of green services. At present, the incentives are extended to December 31, 2025 for application under the allocation of Malaysia's Budget 2023.

Environmental management services such as scheduled waste management services are eligible activities for the following incentives: [6, 7, 8]

[6] MIDA, *Investment in the Services Sector. Booklet 7: Environmental Management Services*, 2020, 15-16.
[7] MIDA, *List of Promoted Activities & Products which are Eligible for Consideration of Pioneer Status and Investment Tax Allowance under the Promotion of Investment Act 1986*, 2020, 4.
[8] IRB, *Accelerated Capital Allowance Public Ruling No. 6/2022,* 7-8.

1. **Incentives for Waste Recycling Activities**
   Companies undertaking environmental management activities are eligible for incentives of "Pioneer Status" or "Investment Tax Allowance (ITA)" through MIDA submission. These activities which include the recycling of waste such as toxic and non-toxic waste, chemical and reclaimed rubber.

2. **Exemption from Import Duty on Machinery and Equipment**
   An exemption from import duty can be considered for the imported machinery and equipment that are used for the provision of waste management services, provided the machinery/equipment are not available locally. The submission shall be provided to MIDA.

3. **Accelerated Capital Allowance for Environmental Management**
   Companies involved in recycling of waste which has incurred qualifying expenditure (QE) on assets used for eligible business purposes may claim accelerated capital allowance (ACA) from the Inland Revenue Board of Malaysia (IRBM).

2.2.7 Environmental, Social and Governance Framework

The implementation and development of Environmental, Social, and Governance (ESG) framework in Malaysia represents a strategic imperative in aligning business practices with global sustainability goals. This framework provides a structured approach to evaluating and improving the performance of businesses in areas crucial to sustainable development.

Specific to the industrial sector, MITI targets to launch the National Industry Environmental, Social and Governance (i-ESG) Framework by 2024. The framework is aimed to provide clear guidelines and enablers for the manufacturing sector to embrace ESG practices, including small medium enterprises (SMEs).

At present, the Bank Negara Malaysia has implemented three (3) ESG-related frameworks which act as guidance for the banking sector, the Climate Change and Principle-based Taxonomy (CCPT), Value-based Intermediation Financing and Investment Impact Assessment Framework (VBIAF), Task Force on Climate-related Financial Disclosure (TCFD). The imposition of ESG frameworks and practice on financial institutions are likely to have cascading effect across the value chain sector, accelerating the ESG adoption across the various economic development sectors.

2.3 ENVIRONMENTAL QUALITY ACT 1974 AND RELEVANT REGULATIONS OR ORDERS THEREUNDER

2.3.1 Environmental Quality Act 1974 (Act 127)

The Environmental Quality Act (EQA) 1974 (Act 127) serves as a framework for the prevention, abatement, control of pollution, and enhancement of the environment, and is overseen by the Department of Environment (DOE). Enacted in 1975, the EQA 1974 has undergone several amendments to align with the international standards.[9]

The EQA 1974 encompasses multiple sections aimed at preventing and regulating pollution, especially in the context of prescribed premises and prescribed conveyances. As stipulated in Section 18 of the EQA 1974, prescribed premises (as defined in **Chapter 2.3.1.2**) are only allowed to operate with a license from DOE.

Furthermore, Section 19 of the EQA 1974 mandates that all prescribed premises and prescribed conveyances shall obtain written permission from the Director General before constructing any structure or facility for the management of scheduled waste or engaging in the transportation of scheduled waste.

To strengthen environmental safeguards, Section 34B of the EQA 1974 establishes stringent prohibitions against activities related to the placement, deposit, or any actions concerning scheduled wastes. These measures collectively serve to ensure that waste management activities are carried out responsibly and in compliance with environmental regulations.

Other relevant legislations include, but are not limited to, the following:

- Environmental Quality (Prescribed Premises) (Scheduled Wastes Treatment and Disposal Facilities) Order 1989 (Amendment 2006).
- Environmental Quality (Prescribed Premises) (Scheduled Wastes Treatment and Disposal Facilities) Regulations 1989.
- Environmental Quality (Prescribed Conveyance) (Scheduled Wastes) Order 2005.
- Environmental Quality (Scheduled Wastes) Regulations 2005 (Amendment 2007).
- Environmental Quality (Industrial Effluent) Regulations 2009.
- Environmental Quality (Clean Air) Regulations 2014.
- Environmental Quality (Prescribed Activities) (Environmental Impact Assessment) Order 2015.

The following Chapters will offer concise summaries of the listed legislations, focusing on information relevant to scheduled waste management. These summaries should not be taken out of context, and in the case of any contradictory statements, the actual legislation should be consulted for reference.

[9] N Artika, Yusof and N Faiza, *An Overview of Scheduled Wastes Management in Malaysia,* JWBM, 2019.

2.3.1.1 Environmental Quality (Prescribed Premises) (Scheduled Wastes Treatment and Disposal Facilities) Order 1989 (Amendment 2006)

The prescribed premises for scheduled wastes treatment and disposal facilities and their definition as listed under this order are:

a) **Off-site storage facilities:** premises occupied or used for the storage, collection or transfer of any scheduled waste which is not produced on those premises;
b) **Off-site treatment facilities:** premises occupied or used for the processing of any scheduled waste which is not produced on those premises;
c) **Off-site recovery facilities:** premises occupied or used for the retrieval of material or product from any scheduled waste which is not produced on those premises;
d) **Scheduled waste incinerators:** premises occupied or used for the thermal destruction of any scheduled waste;
e) **Land treatment facilities:** premises used for the land treatment of any scheduled waste, such as sludge farming; and
f) **Secure landfills:** premises occupied or used for the disposal of any scheduled waste on land.

2.3.1.2 Environmental Quality (Prescribed Premises) (Scheduled Wastes Treatment and Disposal Facilities) Regulations 1989

The prescribed premises as listed and defined in the Environmental Quality (Prescribed Premises) (Scheduled Wastes Treatment and Disposal Facilities) Order, 1989 (Amendment 2006) (**Chapter 2.3.1.1**) are subjected to these Regulations.

These Regulations outline the necessary conditions that shall be met by the facilities engaged in the management of scheduled wastes to prevent adverse environmental impacts, which includes the following:

- Notifying change in information furnished;
- Continuance of existing conditions in case of change in occupancy;
- Inventory of scheduled wastes;
- Measures to be taken where occupier ceases to be the holder of a license;
- Fees for application of written permission and license; and
- Compounding of offences.

2.3.1.3 Environmental Quality (Prescribed Conveyance) (Scheduled Wastes) Order 2005

Based on this order, any vehicle or ship is considered as a prescribed conveyance if it is:

a) Propelled by a mechanism contained within itself;
b) Constructed or adapted to be used on land or water; and
c) Used for the movement, transfer, placement or deposit of scheduled wastes.

The definition of "prescribed conveyance" is significant in the context of waste management and environmental regulations, as it helps to identify and regulate transportation that is used for the movement, transfer, placement, or deposit of scheduled wastes.

2.3.1.4 Environmental Quality (Scheduled Wastes) Regulations 2005 (Amendment 2007)

The Environmental Quality (Scheduled Wastes) Regulations 2005, implemented in Malaysia since August 15, 2005, marked a significant shift from the previous regulations of 1989. These regulations oversee the management of scheduled wastes, with a particular amendment pertaining to waste containing aluminium in 2007.

Within these Regulations, waste generators are allowed to store scheduled wastes generated by themselves within their premises for up to 180 days from the date of generation, provided the quantity does not exceed 20 metric tonnes. Beyond this limit, waste generators shall seek written approval from the Director General.

These Regulations also impose strict labelling, container, and storage requirements on waste generators, ensuring safe and responsible waste management. Furthermore, the regulations grant waste generators the option to apply for Special Management of scheduled wastes, allowing the wastes to be treated, disposed of or recovered at non-prescribed premises or on-site treatment or recovery facilities. These regulations reflect Malaysia's commitment to managing scheduled waste in an environmentally responsible and sustainable manner, aligning with broader efforts to safeguard the nation's natural resources and protect the environment for future generations.

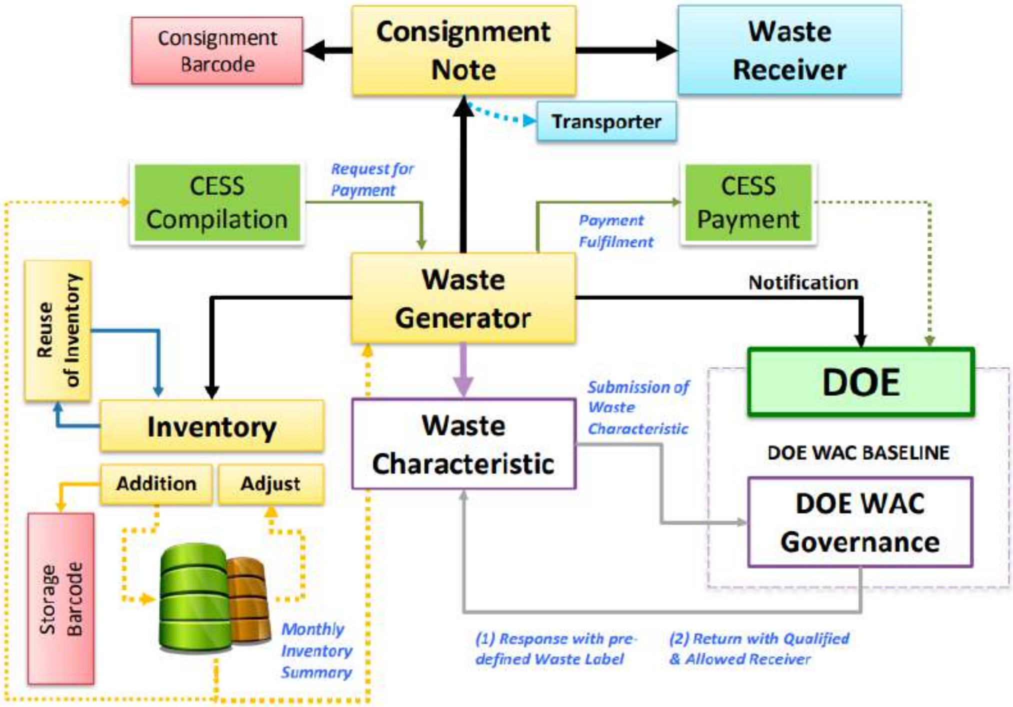
Figure 2-2: eSWIS

eSWIS
Electronic Scheduled Waste Information System

The introduction of the Electronic Scheduled Waste Information System (eSWIS) further streamlined scheduled waste management, enhancing the overall effectiveness of waste management practices in Malaysia (**Figure 2-2**). It is an Environmental Mainstreaming Tool for Guided Self-Regulation, in which the purposes are to:

- Facilitate waste generators to periodically report scheduled waste handling in terms of wastes generation, inventory and the movement and handling of scheduled waste as required under the Environmental Quality (Scheduled Wastes) Regulations 2005 (**Figure 2-3**);

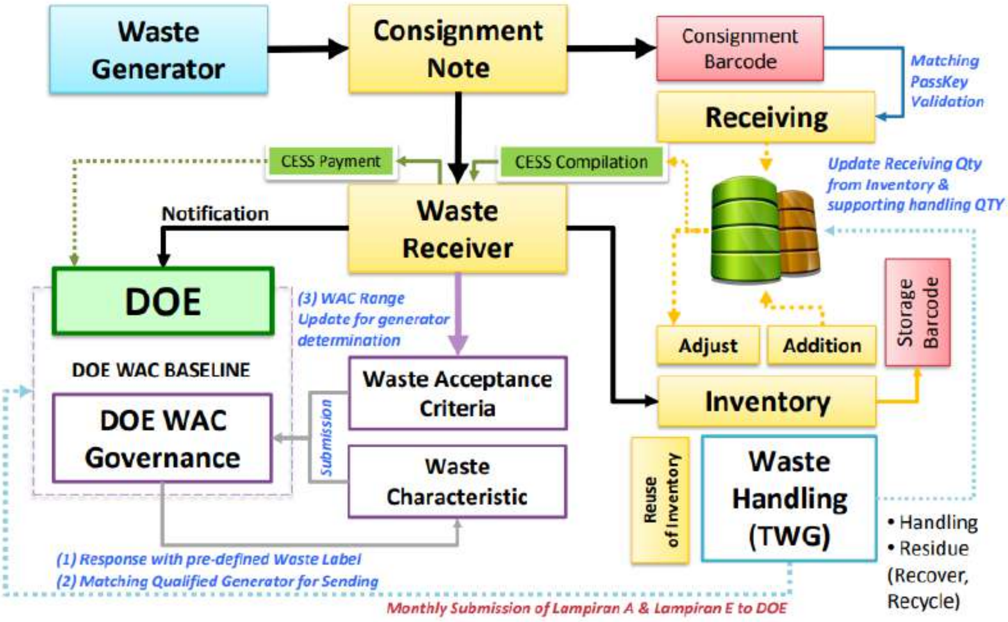
Figure 2-3: Generator-Focus eSWIS Operation Framework[10]



- Facilitate waste generators to ensure compliance of scheduled waste storage as required under the Environmental Quality (Scheduled Wastes) Regulations 2005; and
- Facilitate waste receivers to periodically report scheduled waste handling in terms of wastes received, stored, processed and residual generation as required under the Environmental Quality (Prescribed Premises) (Scheduled Waste Treatment and Disposal Facilities) Regulations 1989 (**Figure 2-4**)

[10] Department of Environment, *Objective & Purpose of eSWIS,* 2017, 33.

Figure 2-4: Receiver-Focus eSWIS Operation Framework[11]



2.3.1.5 Environmental Quality (Industrial Effluent) Regulations 2009

These Regulations are applicable to any premises that release industrial effluent or mixed effluent into soil or inland waters. Prescribed premises that could potentially create a new source of industrial effluent discharge shall submit prior written notification to the Director General, following the stipulations outlined in this document. The Regulations outline specific procedures for designing and constructing industrial effluent treatment systems and the acceptable conditions for discharging industrial or mixed effluent as listed in the Fifth Schedule of the Regulations (**Table 2-1**).

Table 2-1: Acceptable Conditions for Discharge of Industrial Effluent or Mixed Effluent of Standards A and B[12]

Pollutant	Unit	Standard[13]	
		A	B
Temperature	°C	40	40
pH Value	-	6.0-9.0	5.5-9.0
BOD_5 at 20°C	mg/L	20	50
Suspended Solids	mg/L	50	100
Mercury	mg/L	0.005	0.05
Cadmium	mg/L	0.01	0.02
Chromium, Hexavalent	mg/L	0.05	0.05
Chromium, Trivalent	mg/L	0.20	1.0
Arsenic	mg/L	0.05	0.10
Cyanide	mg/L	0.05	0.10

[11] ibid, 34.
[12] *Environmental Quality (Industrial Effluent) Regulations 2009*, Fifth Schedule.
[13] Refer to the Sixth Schedule of the Environmental Quality (Industrial Effluent) Regulations 2009 for catchment areas where Standard A applies.

Pollutant	Unit	Standard[13]	
		A	B
Lead	mg/L	0.10	0.5
Copper	mg/L	0.20	1.0
Manganese	mg/L	0.20	1.0
Nickel	mg/L	0.20	1.0
Tin	mg/L	0.20	1.0
Zinc	mg/L	2.0	2.0
Boron	mg/L	1.0	4.0
Iron (Fe)	mg/L	1.0	5.0
Silver	mg/L	0.1	1.0
Aluminium	mg/L	10	15
Selenium	mg/L	0.02	0.5
Barium	mg/L	1.0	2.0
Fluoride	mg/L	2.0	5.0
Formaldehyde	mg/L	1.0	2.0
Phenol	mg/L	0.001	1.0
Free Chlorine	mg/L	1.0	2.0
Sulphide	mg/L	0.50	0.50
Oil and Grease	mg/L	1.0	10
Ammoniacal Nitrogen	mg/L	10	20
Colour	ADMI[14]	100	200

Additionally, the Regulations encompass various aspects such as monitoring the discharge of industrial or mixed effluent, performance monitoring of the effluent treatment system, specifying the point of discharge, establishing measures for containing spills or accidental effluent releases, prohibiting the discharge of industrial effluent containing certain substances, imposing restrictions on sludge discharge into land or inland waters, and defining penalties for non-compliance, among other provisions.

2.3.1.6 Environmental Quality (Clean Air) Regulations 2014

These Regulations are established in accordance with the Environmental Quality Act 1974 (Act 127) to control:

a) Any premises used for any industrial or trade purposes, or on which matter is burnt in connection with any industrial or trade purposes, including burning of waste, whether or not the premises are prescribed under Section 18 of the Act;
b) Any other premises or process that discharges or is capable of discharging air pollutants into the open air;
c) Any industrial plant; and
d) Any fuel burning equipment.

[14] ADMI: American Dye Manufacturers Institute.

Any scheduled waste facility, including scheduled waste incineration, is one of the activities listed in the First Schedule of these Regulations. According to Section 6 of the Regulations, an owner or occupier of a premises involved in any activity or industry listed in the First Schedule shall incorporate measures to reduce the emission of air pollutants to the atmosphere in accordance with the Best Available Techniques Economically Achievable determined by the Director General.

Specifically, the emission of air pollutants from the incineration process shall not exceed the concentration limits outlined in Table K of the Third Schedule within the Regulations, where the O_2 reference content is 11% (**Table 2-2**). It is also important to note that all installations or activities within the scheduled waste management facility shall adhere to the relevant stipulated limits detailed in the Third Schedule of these Regulations.

Table 2-2: Air Pollutant Emission Limits for Waste Incinerators in All Sizes[15]

Pollutant	Limit Value	Monitoring[16]
Total PM	100 mg/m^3	Continuous
NMVOC as total organic carbon	10 mg/m^3	Continuous
Hydrogen chloride (HCl)	40 mg/m^3	Continuous
Hydrogen fluoride (HF)	1 mg/m^3	Continuous
Sum of SO_2 and SO_3 expressed as SO_2	50 mg/m^3	Continuous
Sum of NO and NO_2 expressed as NO_2	200 mg/m^3	Continuous
Carbon monoxide (CO)	50 mg/m^3	Continuous
Cadmium and its compounds, expressed as cadmium (Cd) Thallium and its compounds, expressed as thallium (Tl)	Total 0.05 mg/m^3	Periodic
Mercury and its compounds, expressed as mercury (Hg)	0.05 mg/m^3	Periodic
Antimony (Sb), Arsenic (As), Lead (Pb), Chromium (Cr), Cobalt (Co), Copper (Cu), Manganese (Mn), Nickel (Ni), Vanadium (V), and their compounds expressed as the element	Total 0.5 mg/m^3	Periodic
PCDD/PCDF	0.1 ng TEQ/m^3	Periodic

The owner or occupier of the said premises are also required to comply with Section 12 of the Regulations, in which the regulation sets opacity limits for emissions, mandates transmissometer installation for certain premises emitting dust, and provides certain exemptions, i.e., for start-up situations.

Moreover, the Regulations mandate that the facility, including the air pollution control system, shall comply with specifications established by the Director General. The Regulations also encompass various aspects, including the performance monitoring of air pollution control systems, record-keeping obligations, requirement for stack monitoring, and provisions for offenses and associated penalties.

[15] *Environmental Quality (Clean Air) Regulations 2014*, Third Schedule, Table K.
[16] Averaging time for continuous monitoring is 30 minutes.

2.3.1.7 Environmental Quality (Prescribed Activities) (Environmental Impact Assessment) Order 2015

Scheduled waste management facilities are also listed as prescribed activities in this Order. Prescribed activities are activities specified in the First Schedule and Second Schedule in the Order and are required to undergo an Environmental Impact Assessment (EIA) which is subjected to the approval of the Director General prior to any commencement of construction works. The preparation of EIA for scheduled waste management facilities can be based on the EIA Guidelines for Waste Treatment and Disposal – Scheduled Waste published by the DOE in 2021.

The applicable prescribed activities for scheduled waste management facilities include, [17] but not limited to, the following:

First Schedule

14. Waste Treatment and Disposal:
(a) Scheduled waste:
- (i) Construction of recovery plant (off-site)
- (ii) Construction of wastewater treatment plant (off-site)
- (iii) Construction of storage facility (off-site)

Second Schedule

14. Waste Treatment and Disposal:
(a) Scheduled waste:
- (i) Construction of thermal treatment plant
- (ii) Construction of off-site recovery plant for lead acid battery wastes
- (iii) Construction of off-site recovery plant or treatment facility that generates significant amount of wastewater which is located at the upstream of public water supply intake
- (iv) Construction of secure landfill facility

2.4 OTHER RELEVANT REGULATIONS

2.4.1 Customs (Prohibition of Imports) Order 2023

This Order came into operation on 15 April 2023, detailing the list of goods that are absolutely prohibited and under conditional prohibition to be imported, as well as any exemptions specified in the Order.

[17] For a full list of prescribed activities, the Environmental Quality (Prescribed Activities) (Environmental Impact Assessment) Order 2015 should be referred.

In the Third Schedule of the Order, under Part I, toxic and/or hazardous wastes from all countries are listed as goods are prohibited to be imported into Malaysia, unless the import is accompanied by a letter of approval issued by or on behalf of the Director General of Environmental Quality, Malaysia. The application for the importation of scheduled waste into Malaysia shall be made via the submission of AS 14 (Rev. 2006) Form (**Appendix A**).

Other examples of prohibited or conditionally prohibited goods that may be applicable to scheduled waste management facilities, include, but not limited to, the following:

- Mixed waste and scrap of miscellaneous paper or paperboard
- Waste, parings and scrap of plastics
- Stranded wire, cables, cordage, ropes, plaited bands and the like, of aluminium wire (excluding insulated electric wires and cables) of steel reinforced aluminium or of aluminium alloys or not alloyed
- Waste and scrap of metal
    - Ferrous waste and scrap; remelting scrap ingots of iron or steel
    - Copper waste and scrap
    - Aluminium waste or scrap

For the complete list of goods prohibited and conditionally prohibited for import and their related information, the Customs (Prohibition of Imports) Order 2023 shall be referred.

2.4.2 Customs (Prohibition of Exports) Order 2023

Similar to the Customs (Prohibition of Imports) Order 2023, this Order also came into operation on 15 April 2023. The Order includes a list of goods subject to either complete prohibition or conditional prohibition on export, along with any exemptions outlined within the Order.

Toxic and/or hazardous wastes from all countries are listed under Part I of the Third Schedule, which indicates that these wastes are considered as goods which is prohibited for export unless the export is accompanied by a letter of approval issued by or on behalf of the Director General of Environmental Quality, Malaysia. The application for export of scheduled waste from Malaysia shall be made via the submission of AS 15A (Rev. 2006) Form (**Appendix B**).

Some examples of other wastes that are prohibited or conditionally prohibited for export listed in the Order includes the following:

- Cement clinker
- Waste and scrap:
    - Of iron and steel
    - Of copper
    - Of nickel
    - Of aluminium
    - Of lead
    - Of zinc
- Recovered (waste and scrap) paper or paperboard
- Used television including video or visual display with TV tuner
- Used washing machine including both wash and dry
- Used cloth dryers (on rack located)
- Used refrigerator including freezer, minibar
- Used air conditioner (32,000 BTU/hr and below)
- Used personal computer
- Used handphone, mobile phone

For the complete list of goods prohibited and conditionally prohibited for export and their related information, the Customs (Prohibition of Exports) Order 2023 shall be referred.

2.4.3 Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal

The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal is an international treaty that provides an obligation to control the transboundary movements and disposal of hazardous wastes. It was adopted on March 22, 1989, in response to growing concerns about the discovery of toxic waste deposits in Africa and other developing regions during the 1980s.

This concern arose due to increasing environmental awareness and stricter regulations in industrialized countries, which led to resistance against hazardous waste disposal, higher disposal costs, and a search for cheaper disposal options in Eastern Europe and the developing world, where environmental regulations were less stringent. The convention came into effect in 1992.

Malaysia has become a party of the Basel Convention on 8th October 1993, and the Department of Environment (DOE) is the designated competent authority of Basel Convention in Malaysia.

As a Party to the Basel Convention, Malaysia has the responsibility to ensure all the provisions of the Convention are fully complied. Therefore, the national policy regarding the transboundary movements of hazardous wastes is as per below:

a) Any importation of hazardous wastes for recovery or final disposal purposes is prohibited;
b) The importation of hazardous wastes is only allowed for the purpose of direct reuse or as alternative raw material provided the hazardous waste is not available in the country;
c) The exportation of hazardous wastes is allowed subjected to the following conditions:
    - The importing country has better technology than the technologies available in Malaysia;
    - The technology in the importing country will result in higher recovery rate than the local recovery facilities; or
    - No technical capacity or facility that is capable to recover the wastes in Malaysia.

Malaysia does not allow any importation of hazardous wastes from any party or member of Organization for Economic Co-operation and Development (OECD), European Commission (EC) and Liechtenstein, in accordance to the Ban Amendment, Basel Convention.

3 OVERVIEW OF SCHEDULED WASTE MANAGEMENT IN MALAYSIA

CHAPTER 3

OVERVIEW OF SCHEDULED WASTE MANAGEMENT IN MALAYSIA

3.1 INTRODUCTION

The concept of scheduled waste management, i.e., reuse, recovery, treatment and final disposal, is not foreign in Malaysia. Throughout the years, Malaysia has developed Regulations and Orders dealing with scheduled wastes in Malaysia, which came into force on 1 May 1989.

Scheduled waste management facilities in Malaysia are considered as Prescribed Premises, where the procedures or the manner of operation to which these licensed premises should adhere to the stipulated Environmental Quality (Prescribed Premises) (Scheduled Wastes Treatment and Disposal Facilities) Regulations 1989.

Additionally, the legal framework that governed the monitoring of the facilities is the Environmental Quality (Prescribed Premises) (Scheduled Wastes Treatment and Disposal Facilities) Order in 1989 (Amendment 2006). Apart from Prescribed Premises, scheduled wastes may be treated, disposed of or recovered in premises that acquire written approval under the special management of scheduled wastes. For example, fly ash from coal-fired power plant (SW 104) can be sent to batching plants to be reused as alternative raw material.

The type of scheduled waste facilities and special management applications for the seven (7) selected scheduled wastes are detailed in this Chapter. The seven (7) selected scheduled wastes are:

- SW 103 – Waste of Lithium-Ion (Li-Ion) Batteries
- SW 104 – Silico-Manganese (Si-Mn) Slag from Ferroalloy Industries
- SW 110 – Spent Insulated Copper Wires and Cables
- SW 202 – Spent Catalysts
- SW 204 – Sludge Containing Heavy Metals from Paper Mill
- SW 205 – Waste Gypsum from Chemical Industries
- SW 321 – Rubber or Latex Wastes

3.2 SCHEDULED WASTE MANAGEMENT IN MALAYSIA

3.2.1 Scheduled Waste Management Facilities

Prescribed premises for scheduled waste management are subjected to the operation conditions and requirements under the:

- Environmental Quality (Prescribed Premises) (Scheduled Wastes Treatment & Disposal Facilities) Order 1989;
- Environmental Quality (Prescribed Premises) (Scheduled Wastes Treatment & Disposal Facilities) Regulations 1989;
- Environmental Quality (Scheduled Wastes) Regulations 2005; and
- Environmental Quality (Prescribed Activities) (Environmental Impact Assessment) Order 2015.

These prescribed premises are required to provide information in accordance with the Sixth Schedule of the Environmental Quality (Scheduled Wastes) Regulations 2005 in the form of a scheduled waste database, known as the Electronic Scheduled Waste Information System (eSWIS) maintained by the Department of Environment (DOE). This database documents the operational and monitoring data of licensed scheduled waste management facilities.

Specific to the seven (7) key scheduled wastes, they are each managed by various management facilities with different operation nature. Presently, there are six (6) main categorizations of prescribed premises, in which the list of existing licensed scheduled waste management facilities can be found on DOE's eSWIS platform:

- Off-site storage facilities;
- Off-site treatment facilities;
- Off-site recovery facilities;
- Scheduled waste incinerators;
- Land treatment facilities; and
- Secure landfills.

Effective management of scheduled wastes is crucial for environmental protection and human health. Various technologies have been developed to handle these hazardous materials, encompassing physical, chemical, biological, and thermal methods. Each method targets different aspects of waste treatment, aiming to either separate, transform, detoxify, or reduce the volume and toxicity of these hazardous materials. In Malaysia, licensed scheduled waste facilities employ a range of these advanced technologies to responsibly manage and process these wastes, ensuring compliance with environmental regulations while minimizing their impact on the ecosystem.

The types of scheduled wastes management technologies include physical, chemical, biological and thermal methods:

- **Physical method:** Relies on the physical characteristics of the waste materials in order to separate the hazardous constituents in a waste stream, wherein residues are further treated and ultimately sent for disposal.
- **Chemical method:** Using chemical reagents to change the chemical structure of the constituents, which produces residues that are less hazardous than the original waste generated.
- **Biological method:** Microorganisms degrade or detoxify the hazardous waste components present to less harmful products.
- **Thermal method:** Volume and toxicity of the wastes are reduced significantly using high temperature, generating energy or fuel in the process.

A prescribe premise may utilize one or more combination of technology method, depending on the management technology's process flow, to ensure environmentally sound management of scheduled waste. Some of the examples of management technologies are as detailed in **Figure 3-1**.

Figure 3-1: Examples of Scheduled Waste Management Technologies

Physical Management Technology

- Centrifugation
- Cyclone Separation
- Distillation
- Electrostatic Separation
- Evaporation
- Filtration
- Heavy Media / Sink-and-Float / Gravity Separation
- Ion Exchange
- Magnetic Separation
- Physical Segregation
- Sedimentation

Chemical Management Technology

- Chemical Dehalogenation
- Electrolysis
- Forced Leaching
- Hydrolysis
- Neutralization
- Precipitation
- Solvent Extraction

Biological Management Technology

- Anaerobic Digestion
- Aerobic Digestion
- Bioleaching / Biohydrometallurgical Process
- Bio-Reclamation e.g., Microbial Desulphurisation
- Vermicomposting

Thermal Management Technology

- Calcination
- Pyrometallurgical Process
- Rotary Kiln Incinerators
- Rotary Kiln Pyrolysis Reactors
- Simple Incinerators
- Starved Air / Fixed Hearth / Air Controlled / Pyrolytic Incinerators
- Thermal Oxidation

3.2.2 Special Management of Scheduled Wastes

Under Regulation 7 of the Environmental Quality (Scheduled Wastes) Regulations 2005, a waste generator may apply in writing to have the generated scheduled wastes excluded from being treated, disposed of, or recovered in prescribed premises, subjected to the Director General's approval. The application for special management of scheduled wastes shall refer to the Guidelines for the Application of Special Management of Scheduled Waste.

The DOE oversees the application process for special management of scheduled waste and maintains a database internally. Based on DOE's database, special management that are presently practiced and applied included:

i. For direct reuse (e.g., soil amendment)
ii. For use in backfilling
iii. For the use as alternative raw material in:
   - Production of secondary products (e.g., wood layers, glycerine recovery, tiles, carbon, electrolytes)
   - Production of bricks/cement/aggregate
   - Production of concrete (use as cement additive)
iv. Trial burn for cement plant

3.3 CATEGORIZATION OF SCHEDULED WASTE MANAGEMENT OPERATIONS IN THE CONTEXT OF CIRCULAR ECONOMY FRAMEWORK

The scheduled waste management operations under the purview of DOE included:

- **Prescribed Premises**
    - Off-site storage facilities
    - Off-site treatment facilities
    - Off-site recovery facilities
    - Scheduled waste incinerators
    - Land treatment facilities
    - Secure landfill
- **On-site Facilities**
    - Treatment facilities
    - Recovery facilities
- **Special Management**
- **Prescribed Conveyance**

The conceptualization of the current management operations in accordance with the circular economy framework, i.e., categorization based on reuse, recovery, treatment and final disposal is summarized in **Table 3-1**. It shall be noted that the waste management operations of prescribed conveyance, storage and treatment are interim operations that facilitates the disposal process of scheduled wastes. Prescribed conveyance intersects all three (3) categories, whereas storage and treatment operations may fall under respective categories, based on the nature/intent of the operation on whether they facilitate further reuse, recovery or final disposal.

Table 3-1: Summary of Categorization of Scheduled Waste Management Operations in the Context of Circular Economy Framework

<table>
<tr><th>Category</th><th>Waste Management Operation[18]</th><th>Type of Registered Operation[19]</th><th>Description</th></tr>
<tr><td>Reuse</td><td>Special Management</td><td>• Special management for use as fertilizer/soil conditioner
• Special management for use as neutralizing agent
• Special management for use in backfilling
• Special management for reuse of container</td><td>• Special management of scheduled waste which is considered as reuse operation are those that to be directly reused without pre-processing (without changing the characteristics of waste) for the same or alternative purposes for which it was conceived.
• Example of reuse is direct application of scheduled waste as fertilizer/soil conditioner and neutralizing agent.
• While backfilling is usually conducted in encapsulated form, it is assumed that the core characteristics of waste remains unchanged and hence classifies as reuse operation.</td></tr>
<tr><td rowspan="4">Recovery</td><td>On-site recovery facilities</td><td>-</td><td rowspan="2">• On-site and off-site recovery facilities that conduct recovery operations, which is the retrieval of material or product from scheduled waste.
• Licensed facilities such as ‘partial recovery’, ‘full recovery’ and ‘recovery’ are all considered as recovery operations.</td></tr>
<tr><td>Off-site recovery facilities</td><td>• Off-site recovery facilities
• Off-site partial recovery facilities
• Off-site full recovery facilities</td></tr>
<tr><td>On-site treatment facilities (for further recovery)</td><td>-</td><td rowspan="2">• On-site and off-site treatment facilities, are interim operations that process scheduled waste, i.e., changing the biological or physico-chemical properties of waste. Such interim operations are required prior to reuse, recovery, or final disposal operations.
• Treatment facilities may be required before reuse or recovery operations, such that a suitable waste stream/compound/mixture can be produced for further operations and processes. Treatment facilities with this nature of operation, preparing waste to replace other material</td></tr>
<tr><td>Off-site treatment facilities (for further reuse/recovery)</td><td>• Co-processing</td></tr>
</table>

[18] Current waste management operations under the provisions of Environmental Quality Act 1974.
[19] Current waste management operations documented under the list of licensed facilities from eSWIS and the internal database for special management from regulator’s internal database.

Category	Waste Management Operation[18]	Type of Registered Operation[19]	Description
			in place to serve a useful purpose, shall be considered as recovery operations. • An example of off-site treatment facility as an interim operation to facilitate further reuse/recovery of scheduled waste is a co-processing plant. Co-processing is defined as the use of suitable waste materials in manufacturing processes for the purpose of energy and/or resource recovery and resultant reduction in use of conventional fuels and/or raw materials through substitution[20]. It is important to note that only from the point where scheduled wastes are being reused for co-processing in cement kiln is considered as 'reuse'. Any pre-processing which prepares the scheduled wastes prior to the point of co-processing shall be considered as treatment operations. Pre-processing is usually required to ensure a homogenous waste stream to meets specification for use in a cement kiln.
	Land treatment facilities[21]	-	• Land treatment facilities per its definition[22] does not specify the intent of treatment of scheduled waste, either to recover materials or discard waste. The definition, however, raise a specific example of "sludge farming", which may suggest the intent to use scheduled waste potentially to improve soil conditions and/or provide nutrient for the purpose of farming, an activity that will result in secondary products. • In this context, land treatment facilities shall be considered as recovery operations, as the scheduled waste is serving a useful purpose by

[20] Department of Environment, *Guidelines on Environmentally Sound Co-Processing of Scheduled Wastes in Cement Industry*, 2015.
[21] Land treatment facilities have been made obsolete by the regulator (DOE) due to integrity concerns for environmentally sound disposal.
[22] See note 5.

Category	Waste Management Operation[18]	Type of Registered Operation[19]	Description
			replacing other materials (fertilizer) which would otherwise have been used to fulfil a particular function (soil improvement).
	Off-site storage facilities (for further reuse/recovery)	Off-site storage facilities (for further reuse/recovery)	• Storage facilities are interim operations that hold scheduled waste for a temporary period prior to the waste being transported, treated or disposed. Such interim operations are required prior to reuse, recovery, or final disposal operations. • Storage facilities that are used to hold waste temporarily prior sending to other reuse or recovery operations, shall be considered as recovery operations, as they facilitate waste to replace other material in place to serve a useful purpose (reuse or recovery).
	Special Management	• Special management for the use as alternative raw material ○ Production of secondary products (e.g., wood layers, glycerine recovery, tiles, carbon, electrolytes) ○ Production of bricks/cement/aggregate ○ Production of concrete (use as cement additive) • Special management for trial burn	• Special management of scheduled waste which is considered as recovery operation are those that serves a useful purpose that replace other materials, such as those which are to be used as alternative raw material. • Special management that prepares waste to fulfil the function to replace other materials shall also be considered as recovery operations such as trial burn, a test and trial process conducted by cement plant prior to co-processing to evaluate the suitability to accept a new waste type as alternative fuel for their cement kiln.
Final Disposal	Secure landfills	Secure landfill	• Secure landfill per its definition[23] is intended for disposal of scheduled waste on land and shall be considered as a final disposal operation. • Secure landfill is usually the final disposition site for all scheduled wastes, including those that have undergone any pre-processing (such as residuals from recovery, treatment, incineration facilities) as a

[23] See note 5.

Category	Waste Management Operation[18]	Type of Registered Operation[19]	Description
			requirement to render the waste to be innocuous and safe for landfilling.
	Scheduled waste incinerators	Incinerator	• Scheduled waste incinerator is defined as premises occupied or used for the thermal destruction of any scheduled waste[24]. The term 'thermal destruction' itself suggests the notion to destruct waste for the purpose of removal, such that the process destruct or make inert the schedule wastes for discarding. • Incineration can be carried out with or without energy, where incineration with energy recovery is commonly referred as waste-to-energy. In instances where thermal destruction is used on organic wastes, the physical characteristics and heating values useful as supplementary fuels in industrial boilers, or the heat generated from the incineration can be converted into energy with the use of heat recovery equipment. In the context of waste reporting, incineration with and/or without energy recovery is considered as disposal operation, which aligns to the practice and principles of Basel Convention[25] and sustainability reporting standards (such as Global Reporting Initiative). • The additional resource steps conducted after the energy recovery from scheduled waste incineration disposal operation, as well as material recovery which may be conducted after the incineration disposal operation, shall be considered as recovery operation.

[24] See note 5.
[25] See note 3.

Category	Waste Management Operation[18]	Type of Registered Operation[19]	Description
	On-site treatment facilities (for further disposal)	-	• On-site and off-site treatment facilities like physical-chemical treatment (PCT), incineration and solidification, are interim operations that process scheduled waste, i.e., changing the biological or physico-chemical properties of waste. Such interim operations are required prior to reuse, recovery, or final disposal operations. • Treatment facilities may be required before final disposal operations, such that the waste is rendered innocuous prior to final disposal methods. • Solidification facilities, which is registered as a license category in the eSWIS system is a well-established pre-landfill waste treatment process, suggesting the intent for such operations is to dispose waste through landfilling[26]. • Treatment facilities with this nature of operation, preparing waste for its final disposition, placement or destruction, shall be considered as final disposal operations.
	Off-site treatment facilities (for further disposal)	• Off-site treatment facilities (for further disposal) • Solidification facilities (for further disposal)	
	Land treatment facilities[27]	-	• Land treatment facilities per its definition[28] does not specify the intent of waste management, either to recover materials or discard waste. • Land treatment may refer to a management method of hazardous waste which constitute treatment and final disposal of the waste[29] • In this context, land treatment facilities shall be considered as final disposal operations.

[26] R Malviya and R Chaudhary, *Factors affecting hazardous waste solidification/stabilization: A review*, 2006.
[27] See note 21.
[28] See note 19.
[29] United States Environmental Protection Agency, *Hazardous waste land treatment*, 1983.

Category	Waste Management Operation[18]	Type of Registered Operation[19]	Description
	Off-site storage facilities (for further disposal)	Off-site storage facilities (for further disposal)	• Storage facilities are interim operations that hold scheduled waste for a temporary period prior to the waste being transported, treated or disposed. Such interim operations are required prior to reuse, recovery, or final disposal operations. • Storage facilities that are used to hold waste temporarily prior sending to other final disposal operations, shall be considered as final disposal operations, as they facilitate waste to their final disposition, placement or destruction.
	Special management	• Special management for disposal at sanitary landfill • Special management for disposal through controlled burning	• Special management of scheduled waste which intends to discard scheduled waste shall be considered as a final disposal operation. • Disposal of scheduled waste at sanitary landfill is method to dispose waste at an engineered isolated environment, subjected to the determination that the waste no longer present reuse/recovery potential and the waste characteristic analysis study meets operation and environmental safety requirements of the receiving sanitary landfill, • Disposal of scheduled waste through self-sustained combustion method is a common waste management method to manage explosive or explosive contaminate materials intended for disposal, where the wastes are rendered permanently inert using this method.

3.4 OVERVIEW OF SELECTED SCHEDULED WASTE MANAGEMENT

This Chapter provides an overview on the proper management for the seven (7) selected scheduled wastes. This includes details such as the material extraction and production of the raw materials, consumption and waste generation of the relevant industries, collection and sorting of waste, and management of selected scheduled wastes to ensure circularity.

3.4.1 SW 103 - Waste Lithium-Ion Batteries

3.4.1.1 Overview of Management

This Chapter describes the overview of the management of waste lithium-ion batteries (**Figure 3-2**).

Material Extraction and Production:
The lifecycle of waste lithium-ion batteries begins with the extraction and production of raw materials. These raw materials, which may be sourced locally or through imports, serve as the foundation for manufacturing of various components of battery cells, including the cathode, anode, electrolyte, separator, current collectors, and casings. The lithium batteries, designed to fulfil specific requirements, are then assembled accordingly. The resulting batteries may then be either exported or used for local consumption. Within this assembly process, there is also a potential for an alternative raw material market, with recovered valuable materials and recycled plastics finding their way into the production cycle.

Consumption and Waste Generation:
These lithium-ion batteries, whether locally manufactured or imported, find utility in a wide array of applications, spanning household items, commercial equipment, institutions, and various industries. This covers diverse range of applications, from light and heavy electric vehicles to portable devices such as laptops, mobile phones, and tablets. Over time, some of the devices or equipment may be resold or locally traded for direct reuse; deemed unusable, are categorized as waste. At this stage, waste lithium-ion batteries may adopt one of two pathways: being managed as solid waste, or categorized as scheduled waste, contingent upon specific considerations.

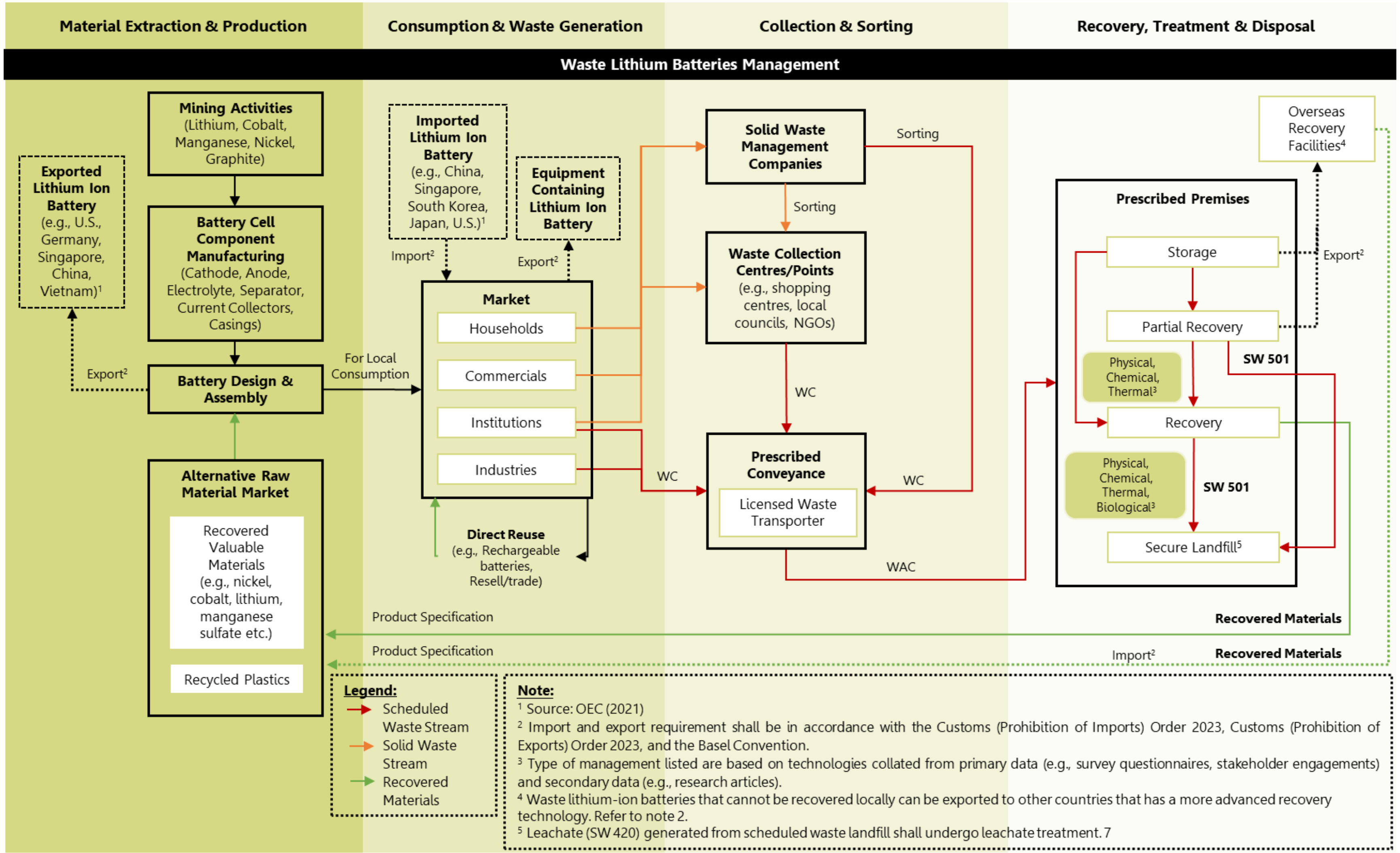
Collection and Sorting:
The collection and sorting of waste lithium-ion batteries in households, commercial areas and institutions predominantly fall under the purview of solid waste management companies. While some individuals may proactively deliver their waste batteries to designated collection centres in shopping complexes, local councils, or non-governmental organizations (NGOs). The bulk of these batteries are typically handled by solid waste management firms. Industries and, to some extent, certain

institutions manage waste lithium-ion batteries as scheduled waste under code SW 103, requires licensed waste transporters for collection.

Recovery, Treatment, and Disposal:
Waste lithium-ion batteries will then be transported to prescribed premises. Storage of waste lithium-ion batteries is generally considered an interim management procedure, with subsequent steps involving further recovery at these prescribed premises.

Some waste lithium batteries will be partially recovered before being exported to recovery facilities in other countries for full recovery, through methods like hydrometallurgy and solvent extraction. The high purity precious materials fully reclaimed from these processes may be imported back into Malaysia and reintroduced into the battery manufacturing industry, contributing to sustainable resource utilization.

Figure 3-2: Value Chain for Waste Lithium-Ion Batteries



3.4.2 SW 104 – Silico-Manganese Slag from Ferroalloy Industries

3.4.2.1 Overview of Management

This Chapter describes the overview of the management of silico-manganese (Si-Mn) slag from ferroalloy industries (**Figure 3-3**).

Material Extraction and Production:
The ferroalloy production process begins with the procurement of raw materials, which can be sourced from manufacturers (e.g., coke) or extracted through mining activities (e.g., limestone, oxide raw materials). These primary raw materials serve as the foundation for the subsequent production phases.

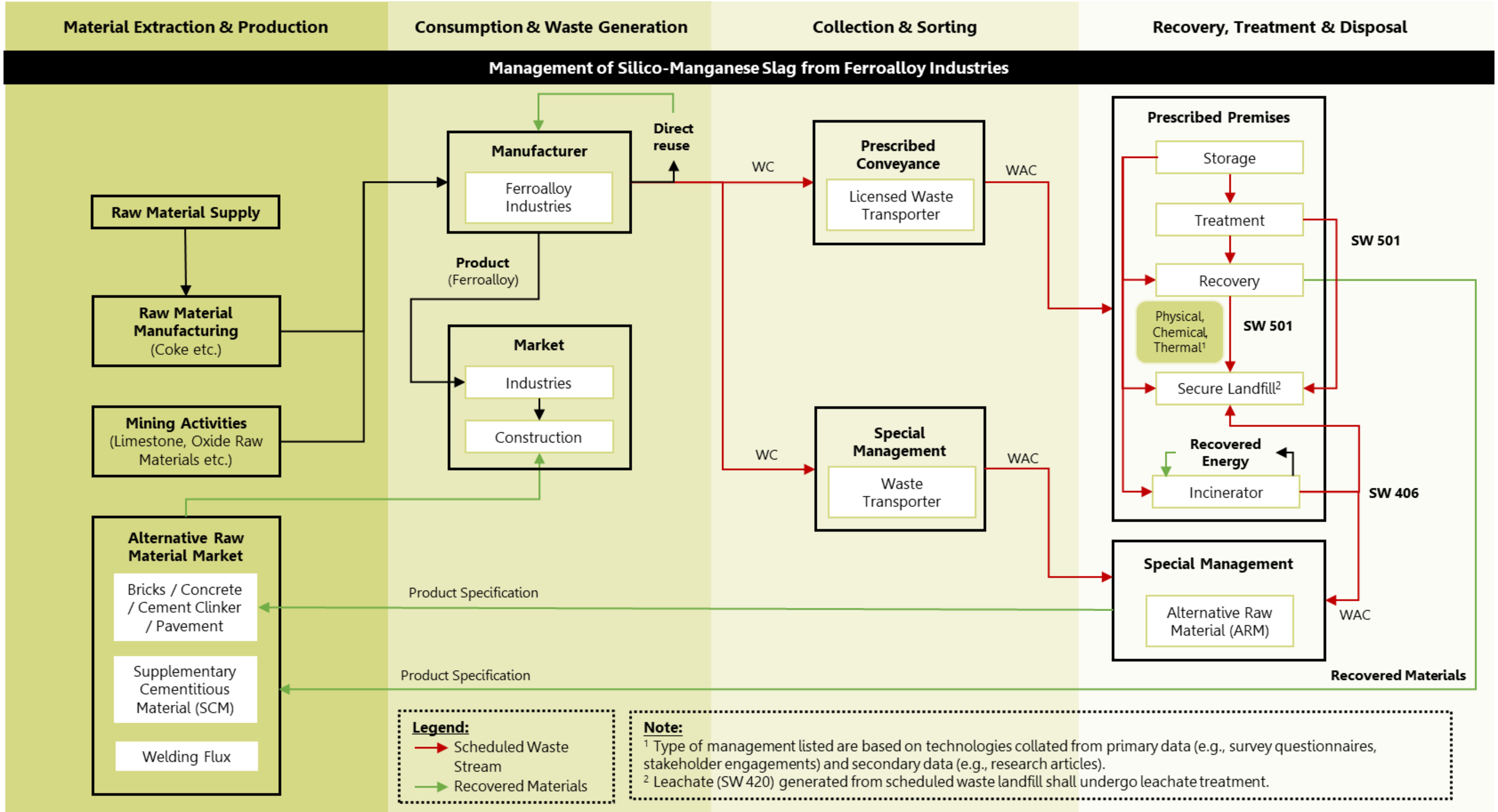
Consumption and Waste Generation:
Ferroalloys find extensive use in iron and steel production, a key industry in the construction sector. During the production of ferroalloys, scheduled wastes like silico-manganese slag (SW 104) will be generated. These residues are a natural outcome of the alloying process. Some of this slag is reused directly into the production cycle, contributing to sustainability efforts.

Collection and Sorting:
Excess slag follows specific waste management protocols. Typically, it will either be directed to designated prescribed premises with the capabilities to manage SW 104 or entrusted to specialized waste transporters for industries that have applied for special management of SW 104.

Recovery, Treatment, and Disposal:
Prescribed premises catering to SW 104 management encompasses a range of facilities, including storage (often serving as an interim operation), treatment, recovery, and incineration units. The treatment and recovery processes may result in the production of SW 501, another scheduled waste category, which will be sent to secure landfills. On the other hand, incineration not only manages waste but also yields recovered energy, other by-products and wastes, including SW 406 which shall also be sent to secure landfills.

Recovery operations for SW 104 are primarily centred around physical, chemical and thermal processes. These processes transform the slag into alternative raw materials suitable for various construction applications. Additionally, silico-manganese slag undergoing special management can be re-purposed as an alternative raw material in the production of construction materials like bricks, concrete, or aggregates. This approach aligns with sustainability goals by minimizing waste and promoting the circular use of resources in the construction sector.

Figure 3-3: Value Chain for Silico-Manganese Slag from Ferroalloy Industries



3.4.3 SW 110 – Spent Insulated Copper Wire and Cable

3.4.3.1 Overview of Management

Overview of spent insulated copper wire and cable management is detailed in **Figure 3-4**.

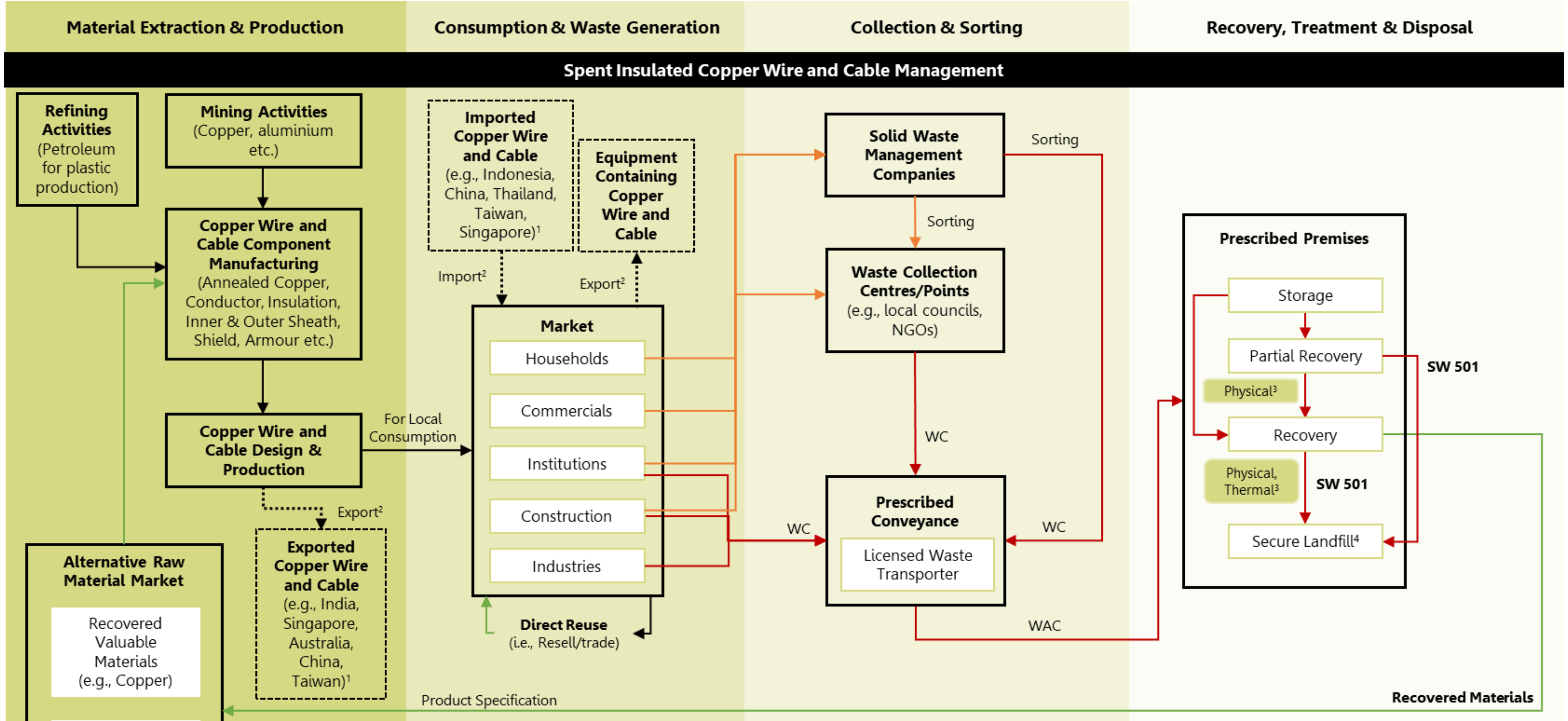
Material Extraction and Production:
The lifecycle of spent insulated copper wires and cables begins with the extraction and production of raw materials. These materials, such as annealed copper, conductors, insulation, sheaths, shields, and armour, form the fundamental components for copper wire manufacturing. After production, these components will be directed to specialized facilities for copper wire and cable design and production. The resulting copper wires and cables may either be exported or used domestically. During assembly, there is potential engagement with alternative raw material markets, including materials recovered from spent insulated copper wire and cables, such as copper and recycled plastics.

Consumption and Waste Generation:
Applications of copper wires and cables span households, commercials, institutions, construction and industries. Over time, copper wires and cables may be resold or locally traded for immediate reuse, while others, deemed unusable, are categorized as waste. At this juncture, spent insulated copper wires and cables can adopt one of two management pathways, contingent upon specific considerations.

Collection and Sorting:
Spent insulated copper wire and cable collection and sorting predominantly involve solid waste management entities, especially in households, commercial areas, institutions, and certain construction sites. While some individuals may choose to transport waste insulators to designated collection points managed by local authorities or non-governmental organizations, established solid waste management companies typically handle the primary sorting and management of these insulators. Additionally, industries, selected construction sites, and specific institutions manage spent insulated copper wires and cables as scheduled waste, under code SW 110, requiring licensed waste transporters for collection.

Recovery, Treatment, and Disposal:
Spent insulated copper wires and cables categorized under SW 110 are transported to prescribed premises. Storage primarily serves as an interim measure, with subsequent stages involving partial recovery through mechanical dismantling and sorting before proceeding to full recovery processes. Valuable materials fully reclaimed from these processes can be re-introduced into the copper wire and cable manufacturing industry, promoting sustainable resource utilization practices.

Figure 3-4: Value Chain for Spent Insulated Copper Wire and Cable



Legend:
- Scheduled Waste Stream
- Solid Waste Stream
- Recovered Materials

Note:
[1] Source: OEC (2021)
[2] Import and export requirement shall be in accordance with the Customs (Prohibition of Imports) Order 2023, Customs (Prohibition of Exports) Order 2023, and the Basel Convention.
[3] Type of management listed are based on technologies collated from primary data (e.g., survey questionnaires, stakeholder engagements) and secondary data (e.g., research articles).
[4] Leachate (SW 420) generated from scheduled waste landfill shall undergo leachate treatment.

3.4.4 SW 202 – Spent Catalysts

3.4.4.1 Overview of Management

This Chapter describes the overview of the management of spent catalysts (**Figure 3-5**).

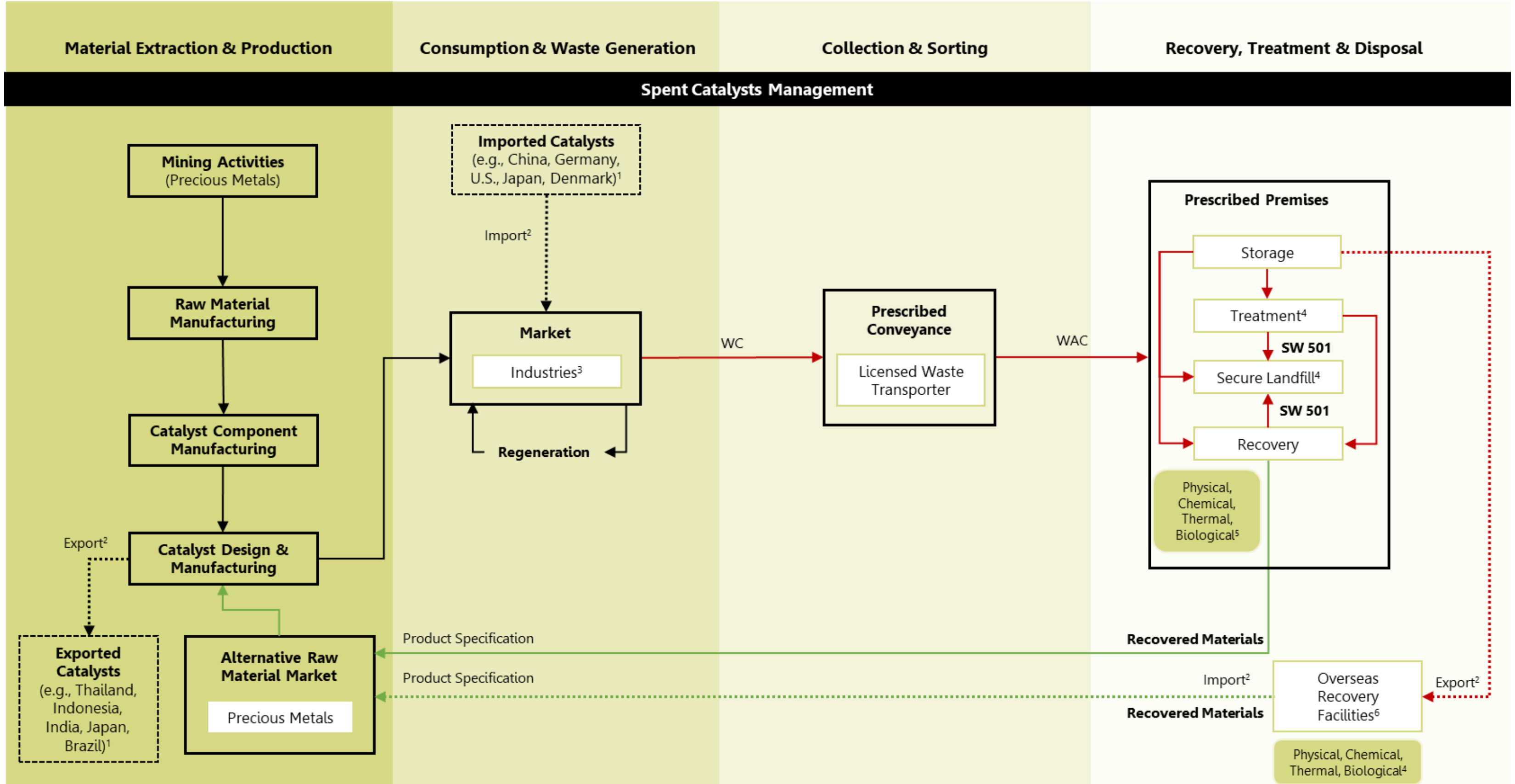
Material Extraction and Production:
The production of catalysts commences with the extraction of raw materials, a process rooted in mining activities that yield precious metals from the earth. These raw materials are then subjected to manufacturing processes tailored to suit catalyst production. Catalysts, designed to fulfil specific industrial requirements, are manufactured accordingly. Notably, a portion of the locally manufactured catalysts finds their way into international markets, with countries like Thailand, Indonesia, and India among the recipients.

Consumption and Waste Generation:
Industries reliant on catalysts encompass petrochemical, oil refining, and chemical sectors. When a catalyst reaches the point where it can no longer fulfil its intended function, it is referred to as a spent catalyst. The management of spent catalysts depends primarily on the chemical structural changes that occur during their use. Several options exist for dealing with spent catalysts, including a method known as regeneration. Regeneration typically involves the removal, often through controlled burning, of surface coatings and absorbed species. From both an environmental and economic perspective, regeneration is generally the preferred choice for managing spent catalysts. It allows for the extended use of the catalyst, reducing the demand for new raw materials and minimizing the necessity for ultimate recovery or disposal.

Collection and Sorting:
Spent catalysts designated for off-site management undergo collection and transportation processes facilitated by licensed waste transporters.

Recovery, Treatment, and Disposal:
Typically, spent catalysts will be directed toward recovery operations aimed at reclaiming precious metals. The recovered precious metals, often of high purity, are subsequently reintegrated into the catalyst manufacturing process, ensuring a sustainable utilization of these valuable resources.

Figure 3-5: Value Chain for Spent Catalysts



Legend:
- Scheduled Waste Stream
- Recovered Materials

Note:
[1] Source: OEC (2021)
[2] Import and export requirement shall be in accordance with the Customs (Prohibition of Imports) Order 2023, Customs (Prohibition of Exports) Order 2023, and the Basel Convention.
[3] Type of industries include petrochemical, oil-refining and chemical industries.
[4] Leachate (SW 420) generated from scheduled waste landfill shall undergo leachate treatment.
[5] Type of management listed are based on technologies collated from primary data (e.g., survey questionnaires, stakeholder engagements) and secondary data (e.g., research articles).
[6] Spent catalysts that cannot be recovered locally can be exported to other countries that has a more advanced recovery technology. Refer to note 2.

3.4.5 SW 204 – Sludge Containing Heavy Metals from Paper Mill

3.4.5.1 Overview of Management

This Chapter describes the overview of the management of paper mill sludges (**Figure 3-6**).

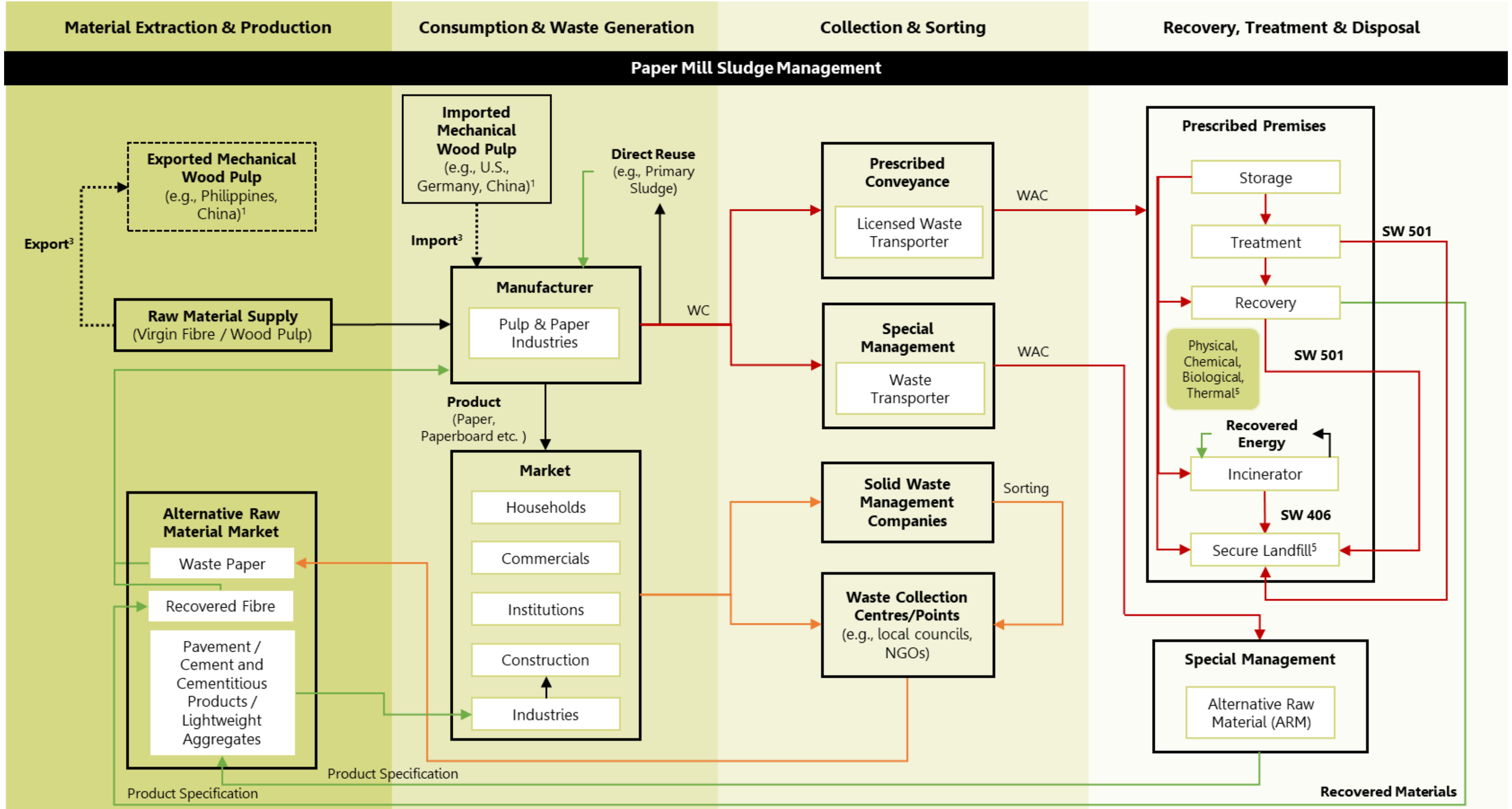
Material Extraction and Production:
In the pulp and paper industry, the production process relies on raw materials like virgin fibre and wood pulp, which can be sourced locally or imported. Additionally, alternative raw materials, including waste paper and recovered fibres, are sometimes used.

Consumption and Waste Generation:
Within pulp and paper mills, the production process generates three (3) main types of sludges: primary sludge, secondary sludge, and wastewater sludge. Notably, sludges characterized by a higher percentage of long fibres, such as primary sludges, often find direct reintegration into the production cycle. Conversely, secondary sludge and wastewater sludge, enriched with shorter and finer fibres, can be repurposed to create lower-grade paper products, including items like egg cartons. Alternatively, these sludges may undergo on-site incineration, contributing to energy recovery for in-house consumption.

Collection and Sorting:
In cases where on-site management is not feasible, portions of the sludges will be transported off-site to prescribed premises by licensed waste transporters. Paper mill sludges can also be managed under Special Management according to the procedures outlined in the Guidelines for the Application of Special Management of Scheduled Waste and will be transported to designated facilities.

Recovery, Treatment, and Disposal:
Off-site management facilities encompass storage, treatment, recovery, and incineration units. Storage facilities often serve as interim measures, temporarily housing scheduled waste before eventual transfer to treatment, recovery, or incineration facilities. Paper mill sludges that are dispatched to recovery facilities, is believed to yield recovered fibre suitable for the production of low-grade paper products.

Figure 3-6: Value Chain for Paper Mill Sludges



Legend:
- Scheduled Waste Stream
- Solid Waste Stream
- Recovered Materials

Note:
[1] Source: OEC (2021)
[2] Source: Trend Economy (2021)
[3] Import and export requirement shall be in accordance with the Customs (Prohibition of Imports) Order 2023 and Customs (Prohibition of Exports) Order 2023.
[4] Type of management listed are based on technologies collated from secondary data (e.g., research articles).
[5] Leachate (SW 420) generated from scheduled waste landfill shall undergo leachate treatment.

3.4.6 SW 205 – Waste Gypsum from Chemical Industries

3.4.6.1 Overview of Management

This Chapter describes the overview of the management of waste gypsum from chemical industries (**Figure 3-7**).

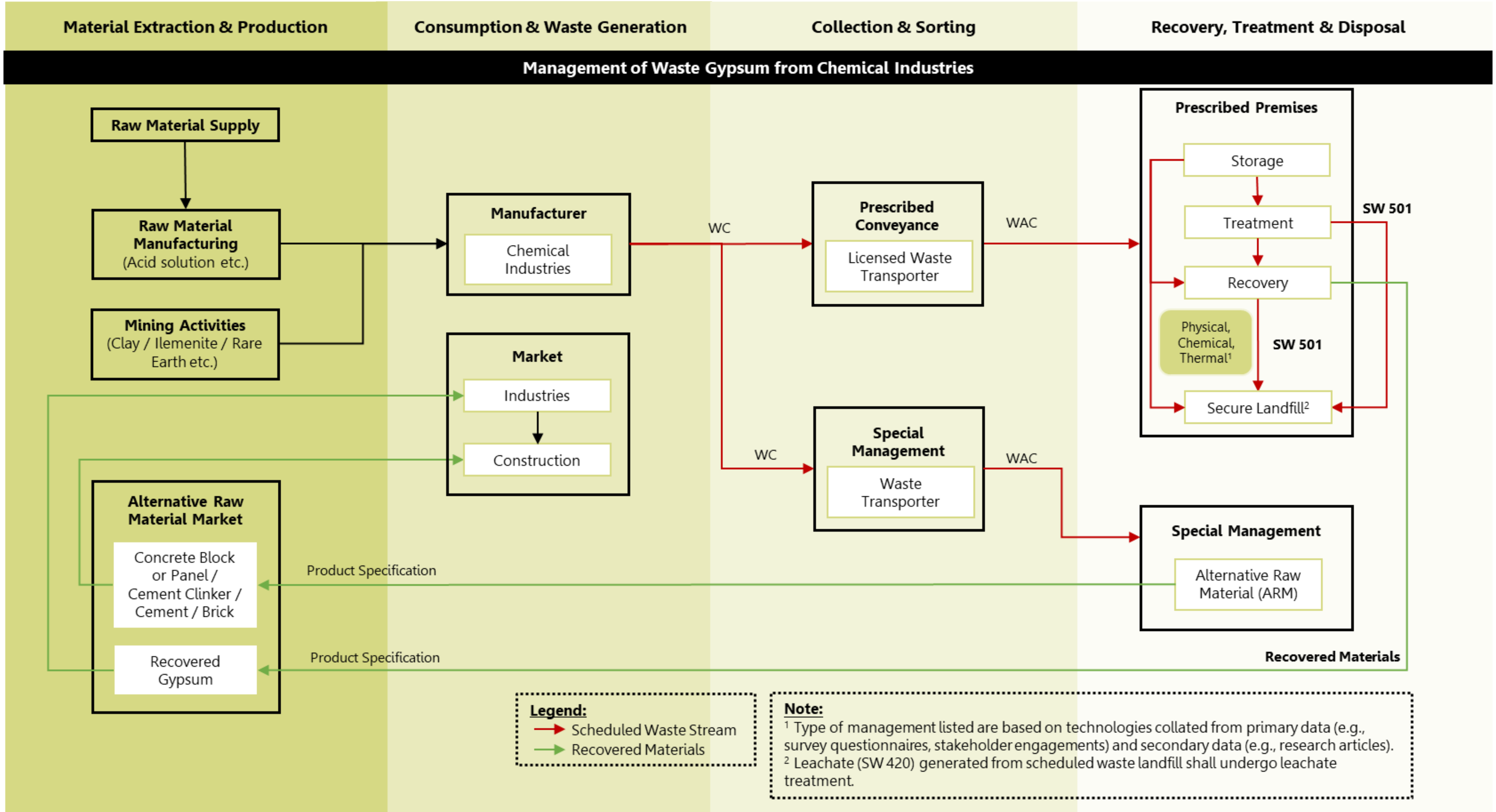
Material Extraction and Production:
Waste gypsum generation in Malaysia primarily stems from chemical industries, particularly those engaged in the production of bleaching earth. These industries rely on raw materials like acid solutions, and also clay, ilmenite, or rare earth elements, which are typically obtained through mining activities.

Consumption and Waste Generation:
The chemical industries generate significant quantities of waste gypsum as a by-product.

Collection and Sorting:
Waste gypsum can be managed through two primary routes: either transported to prescribed premises via licensed waste transporters or subjected to Special Management following approval from the Department of Environment (DOE) through a Special Management Application under the procedures outlined in the Guidelines for the Application of Special Management of Scheduled Waste.

Recovery, Treatment, and Disposal:
In off-site SW 205 management facilities, waste gypsum may undergo various processes. Physically recovered gypsum often serves as a supplementary or alternative raw material in the production of construction materials. Waste gypsum undergoing special management can also be repurposed as an alternative raw material for creating construction components like concrete blocks or panels, actively contributing to the construction industry's resource-efficient practices.

Figure 3-7: Value Chain for Waste Gypsum from Chemical Industries



3.4.7 SW 321 – Rubber or Latex Wastes

3.4.7.1 Overview of Management

This Chapter describes the overview of the management of rubber or latex waste (**Figure 3-8**).

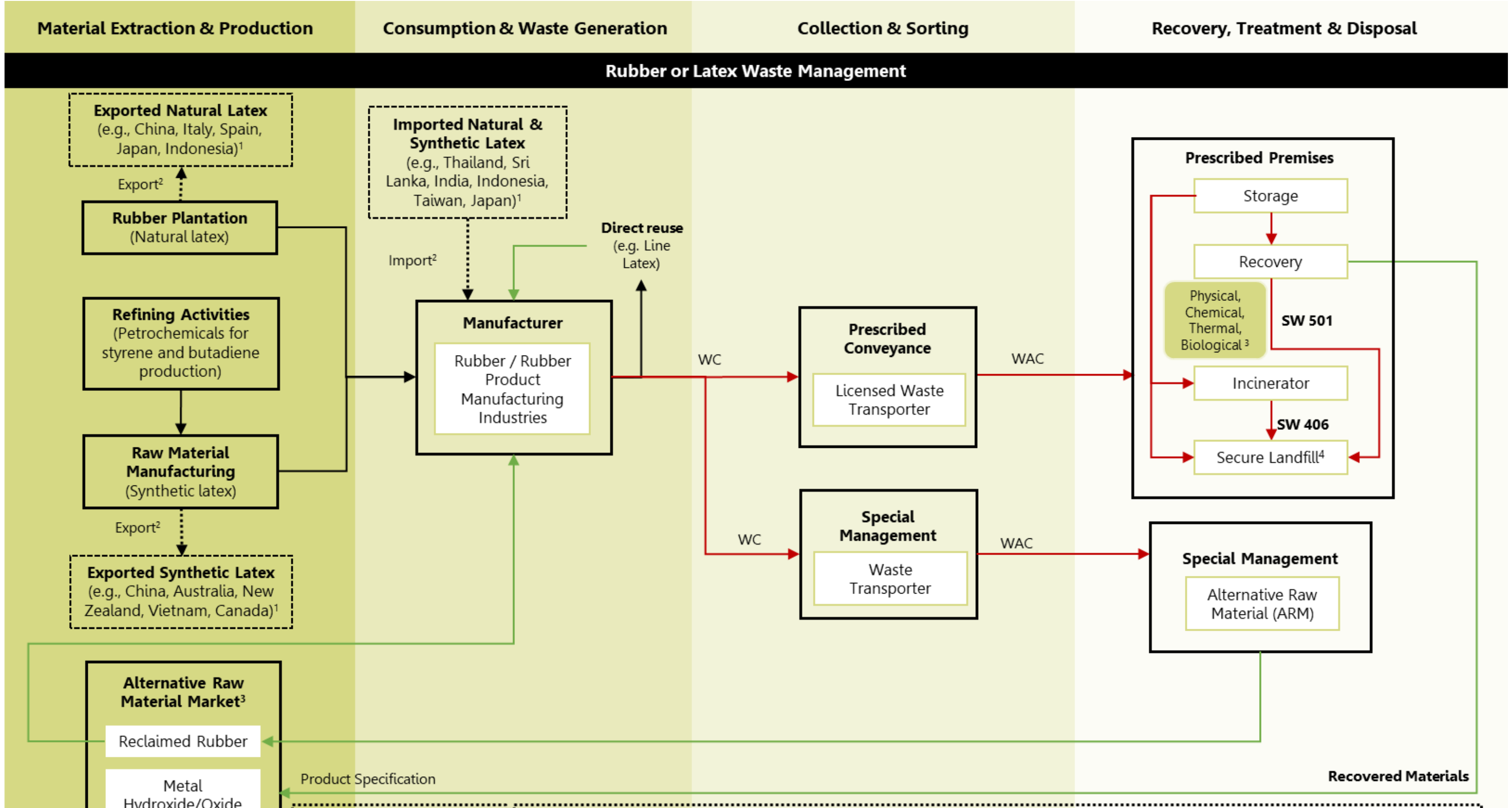
Material Extraction and Production:
The local rubber product manufacturing industries in Malaysia rely on both natural latex sourced from rubber plantations and synthetic latex produced from petrochemicals like styrene and butadiene. These raw materials, whether locally procured or imported, are essential for their production processes. Additionally, Malaysia also exports latex to foreign markets, such as China.

Consumption and Waste Generation:
Efforts within the rubber and rubber product manufacturing sectors prioritize waste reduction, including the recycling of line latex back into the production cycle. Any latex waste generated by these industries is typically subjected to a water-draining (drying) process before being directed to off-site management facilities.

Collection and Sorting:
Licensed waste transporters handle the collection and transportation of latex waste to designated prescribed premises. Rubber or latex waste that have applied for Special Management are transported to designated approved facilities via waste transporter, following the procedures outlined in the Guidelines for the Application of Special Management of Scheduled Waste.

Recovery, Treatment, and Disposal:
These prescribed premises include storage facilities, recovery facilities, and incinerators. Within recovery facilities, latex waste will undergo various physical, chemical, or thermal treatment methods, leading to the production of reclaimed rubber. Additionally, some metal hydroxide/oxide is recovered, primarily through pyrolysis processes. The reclaimed rubber finds applications in the manufacturing of rubber products like shoe soles and rubber mats, contributing to resource efficiency in the rubber industry. For Special Management, rubber or latex waste can be used as an alternative raw material in the production of reclaimed rubber.

Figure 3-8: Value Chain for Rubber or Latex Waste



Note:
[1] Source: OEC (2021)
[2] Import and export requirement shall be in accordance with the Customs (Prohibition of Imports) Order 2023 and Customs (Prohibition of Exports) Order 2023.
[3] Type of management listed are based on technologies collated from secondary data (e.g., research articles).
[4] Leachate (SW 420) generated from scheduled waste landfill shall undergo leachate treatment.

4 REUSE AND RECOVERY OPTIONS OF SELECTED SCHEDULED WASTES

CHAPTER 4

REUSE AND RECOVERY OPTIONS OF SELECTED SCHEDULED WASTES

4.1 INTRODUCTION

The following Chapters will provide insights into the reuse and recovery technologies associated with the seven (7) selected scheduled wastes. These approaches will be presented in accordance with the Environmentally sound management (ESM) hierarchy, prioritising scheduled waste reuse applications and subsequently delving into recovery technologies. A common recovery application for scheduled wastes, namely the co-processing of these wastes in cement plants, will be explored separately.

The exploration of each reuse applications and recovery technologies include the following aspects:

- **Process Description:** Entails a breakdown of the process, including a visual process flow chart that illustrates key elements such as feed, product, by-products, and operating conditions where relevant.
- **Waste Acceptance Criteria (WAC):** Criteria for accepting these scheduled wastes are explained.
- **Advantages and Limitations:** Drawing from findings in relevant literature, this Chapter presents a balanced view of the strengths and weaknesses associated with each circular economy approach.
- **Recommendations and Further Research:** Informed by the studies and research conducted by authors and researchers in the field, this Chapter provides insights into recommended steps or areas for further research necessary prior to commercialization.
- **Current Applications:** Through an amalgamation of literature findings and stakeholder engagement, the current state of implementation of these reuse and recovery options, either on a national or corporate level are highlighted.
- **Technology Readiness Levels (TRLs):** Based on the current application status of each reuse and recovery technology, the Technology Readiness Levels are assigned, giving an indication of the maturity and feasibility of implementation.

Please note that the technologies presented in this Chapter are examples and not an exhaustive list. The field of scheduled waste management is dynamic, continuously introducing new practices and innovations. While this document offers a comprehensive overview, it may not cover all existing reuse applications or recovery technologies. The absence of specific technologies here does not mean they are nonviable. Waste receivers and generators are encouraged to seek diverse options by consulting experts and exploring additional resources for the most current and tailored solutions to meet their waste management needs.

4.1.1 Technology Readiness Levels (TRLs)

Technology Readiness Levels or TRLs is a measurement system used to assess maturity level of a particular technology throughout its research, development and deployment phase progress.[30] Originally devised by the National Aeronautics and Space Administration (NASA) in the 1970s to gauge technology readiness for space missions, TRLs have expanded beyond space exploration.[31] They later gained adoption in various sectors, including the European Union and military organizations worldwide, stemming from mandates within the United States Department of Defense and Commonwealth of Australia in the late '90s and early 2000s.[32]

There is a total of nine (9) TRLs, with one (1) being the least ready, and they can be grouped into three (3) main phases: research, development and deployment (**Table 4-1**). Technologies which are still conceptual and theoretically based are considered as the research phase. Technologies that have been validated and demonstrated but not operational yet, are considered the development phase. Lastly, in the deployment phase, the technology already has a prototype or actual system in an operational environment.

Table 4-1: Technology Readiness Levels (TRLs)[33]

Research	1	**Basic Principles Observed** Scientific observations made and reported. Examples could include paper-based studies of a technology's basic properties.
	2	**Technology Concept Formulated** Envisioned applications are speculative at this stage. Examples are often limited to analytical studies.
	3	**Experimental Proof of Concept** Effective research and development initiated. Examples include studies and laboratory measurements to validate analytical predictions.

[30] C G Manning, *Technology Readiness Levels*, 2023.
[31] TWI Global, *What are Technology Readiness Levels (TRL)*, 2023.
[32] M Héder, *From NASA to EU: the evolution of the TRL scale in Public Sector Innovation*, 2017.
[33] See note 31.

Development	4	**Technology Validated in Lab** Technology validated through designed investigation. Examples might include analysis of the technology parameter operating range. The results provide evidence that envisioned application performance requirements might be attainable.
	5	**Technology Validated in Relevant Environment** Reliability of technology significantly increases. Examples could involve validation of a semi-integrated system/model of technological and supporting elements in a simulated environment.
	6	**Technology Demonstrated in Relevant Environment** Prototype system verified. Examples might include a prototype system/model being produced and demonstrated in a simulated environment.
Deployment	7	**System Prototype Demonstration in Operational Environment** A major step increases in technological maturity. Examples could include a prototype model/system being verified in an operational environment.
	8	**System Complete and Qualified** System/model produced and qualified. An example might include the knowledge generated from TRL 7 being used to manufacture an actual system/model, which is subsequently qualified in an operational environment. In most cases, this TRL represents the end of development
	9	**Actual System Proven in Operational Environment** System/model proven and ready for full commercial deployment. An example includes the actual system/model being successfully deployed for multiple projects by end users.

The reuse and recovery options for the selected scheduled wastes in the following Chapters were assessed on the TRLs based on the input obtained from Focus Group Discussions from the relevant industry players, and research and review articles from desktop studies. It is important to note that the assigned TRLs are evaluated according to the best professional judgement based on available sources.

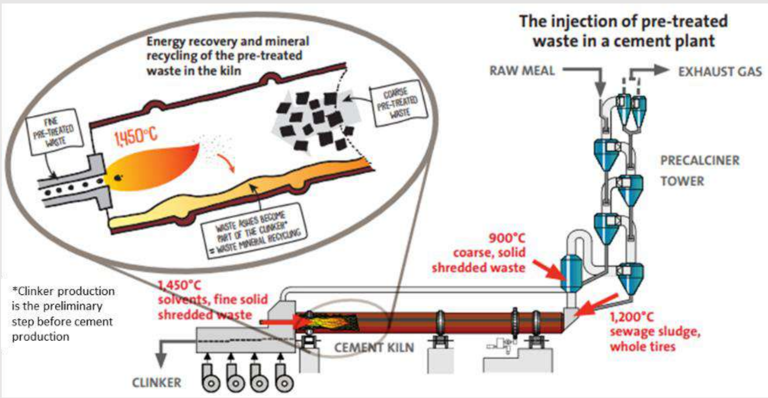
4.2 REUSE AND RECOVERY OPTIONS

4.2.1 Common Recovery Technology (Co-Processing Within Cement Plant)

From the literature review and study on the circular economy approaches, it was found that most of the scheduled wastes selected, e.g., SW 104, SW 110 (spent insulated wire or cable insulator), SW 204, SW 205 and SW 321, can be co-processed within cement plants. Based on the categorization of scheduled waste management operations in the context of circular economy framework, co-processing is categorized under recovery (Refer to **Chapter 3.3**, **Table 3-1**). Co-processing is defined as the use of suitable waste materials in manufacturing processes for the purpose of energy and/or resource recovery and resultant reduction in the use of conventional fuels and/or raw materials through substitution.

The co-processing of scheduled wastes in cement industry should be conducted in accordance with the latest version of the Guidelines on Environmentally Sound Co-Processing of Scheduled Wastes in Cement Industry published by the DOE. The details, e.g., process description and waste acceptance criteria, for co-processing in this Chapter are extracted from the guidelines published by the DOE in 2015 and summarized in the following technology description.

<table>
<tr><td>Technology</td><td>Co-processing within cement plant

Plate 4-1: Cement Plant[34]
</td></tr>
<tr><td>Process Description[35, 36]</td><td>

Portland cement production begins with the manufacture of clinker followed by its fine grinding with gypsum and other additives to make the finished cement product.
Grinding can occur on site or at offside grinding plants known as cement mills.
Clinker manufacture involves the quarrying, crushing, and proportioning of raw materials to produce either a raw meal for the dry and semi-dry processes or a slurry for the wet and semi-wet processes.
Once the material is prepared, the raw material mix is fed into a kiln where it is heated as it moves through a number of chemical and physical processes necessary to form clinker.
</td></tr>
</table>

[34] European Union, *Co-processing of waste in EU cement plants: status and prospects*, 2019.
[35] Geocycle, *Co-processing: a unique waste treatment solution,* undated.
[36] *Annex 1 Clinker Production Process*, undated.

	• In the kiln, the raw meal, or slurry in the wet process, is subjected to a thermal treatment process consisting of the consecutive steps of 'drying/preheating', 'calcining', and 'sintering' (also known as 'burning' or 'clinkering'). • The first drying and preheating zone occurs in a temperature range from <100 to 750˚C, where residual or free water is evaporated from the raw meal feed, clay materials begin to decompose, and the bound water is removed so that they become dehydrated. • Next is the calcining zone, where materials temperatures range from 750 to 1000˚C. • The material is calcined, where $CaCO_3$ in the limestone is dissociated producing CaO and liberating CO_2 gas. • Finally, in the burning zone, CaO reacts with silicates, iron and aluminium to form C_2S, C_3S, C_3A, and C_4AF. • In addition, clinker nodules, typically 3 to 20 mm in diameter, are formed in a semi-solid state in the burning zone, and solidify completely on cooling, which begins in a short cooling zone within the kiln, and continues in a cooler environment, outside of the kiln. • The composition, specifications and conformity criteria for cement should comply with the latest version of MS EN 197.
Waste Acceptance Criteria (WAC)[37, 38]	<u>For alternative raw material (analysis should be in dry basis)</u> • Total of 2 major oxides (i.e., SiO_2, Fe_2O_2, Al_2O_3, CaO) should be > 30% in dry basis • Cl concentration of maximum 2%; waste with total halogenated organic with > 1% shall be used at the main burner only • Moisture content of ≤ 70% in waste (subjected to the characteristics of the waste) • Total heavy metals (i.e., Pb, Cr, As, Sn, Se, Ni, Te, Co, V, Sb, Mn) should be ≤ 100,000 ppm • Zn concentration < 30,000 ppm in total input • Cu concentration < 30,000 ppm in total input • Hg concentration < 10 ppm • Total volatile metal (i.e., Hg, Ti and Cd) should be ≤ 100 ppm • Total organic content <1% if ARM is fed in cold part of the process <u>For alternative fuel (analysis should be in ash basis)</u> • Cl concentration of maximum 2%; waste with total halogenated organic with > 1% shall be used at the main burner only • Moisture content of ≤ 70% in waste (subjected to the characteristics of the waste)

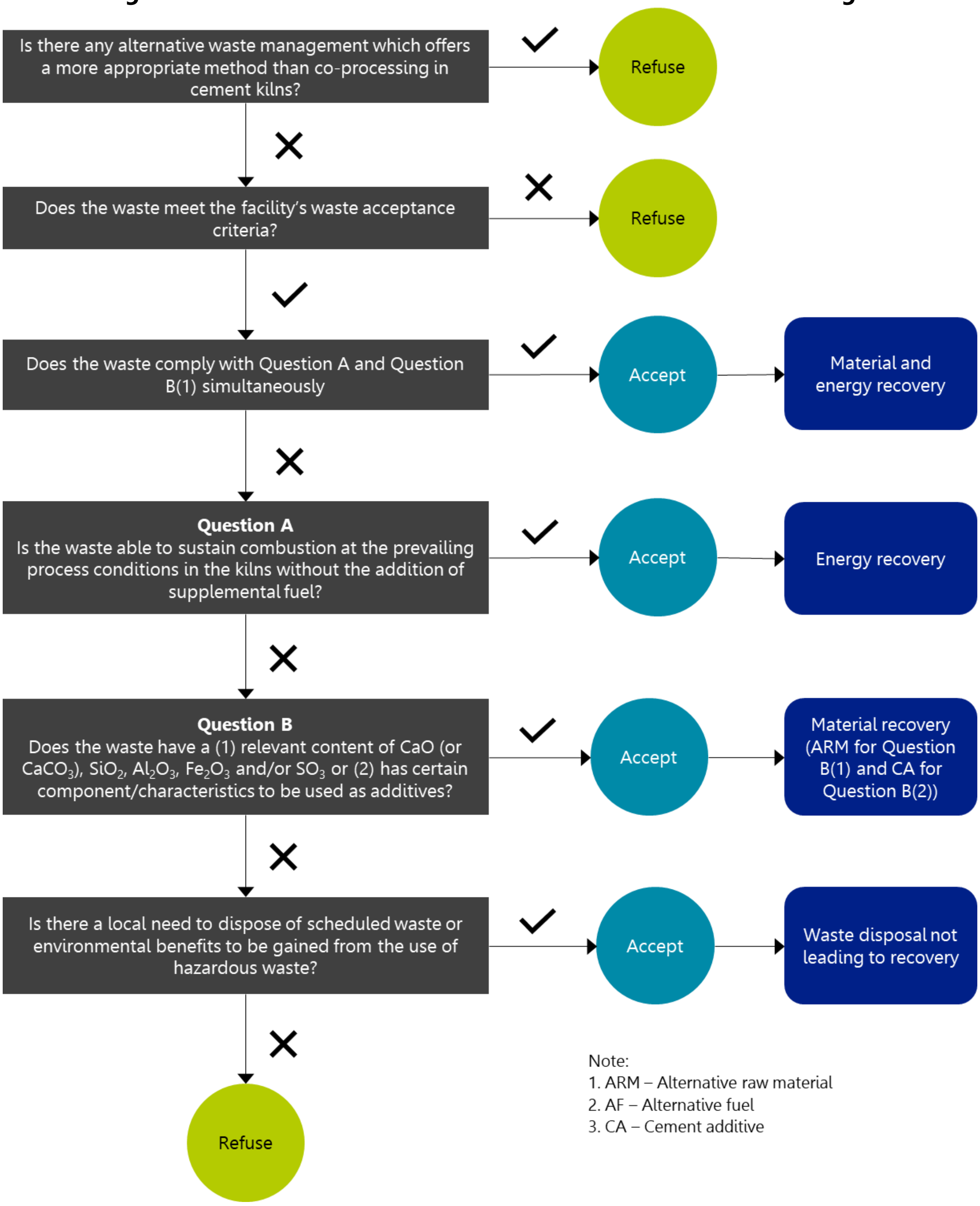
[37] Department of Environment, *Guidelines on Environmentally Sound Co-Processing of Scheduled Wastes in Cement Industry*, 2015, 22-24.

[38] WAC shall always be up to date with the values published in the latest version of *Guidelines on Environmentally Sound Co-Processing of Scheduled Wastes in Cement Industry.*

	• Total heavy metals (i.e., Pb, Cr, As, Sn, Se, Ni, Te, Co, V, Sb, Mn) should be ≤ 100,000 ppm • Zn concentration < 30,000 ppm in total input • Cu concentration < 30,000 ppm in total input • Hg concentration < 10 ppm • Total volatile metal (i.e., Hg, Ti and Cd) should be ≤ 100 ppm • Calorific heating value > 500 kcal/kg (as dried basis) For cement additive • Low content of organic carbon • Does not contain radioactive component
Advantages	• Co-processing helps to partially replace conventional fuels in the cement kiln, such as coal or pet coke
Limitations	• Cement kilns may emit pollutants while using alternative fuels
Recommendations/ Further Research Required	Further research is required before implementation
Current Application	Practiced by local and overseas cement industries
Technology Readiness Levels (TRLs)	9 (Actual system proven in operational environment)

The general decision (accept-refuse) process to distinguish between operations that lead to scheduled wastes being co-processed in a cement plant rotary kiln is illustrated in **Figure 4-1**.

Figure 4-1: Decision Flowchart for Scheduled Waste Co-Processing[39]



4.2.2 SW 103 – Waste Lithium-Ion Batteries

The scheduled waste code SW 103 consists of waste of batteries that contain nickel and cadmium or mercury or lithium. Rechargeable batteries are the most widely used battery type in both industrial and household settings which includes lithium-ion, alkaline nickel-cadmium, nickel-metal hydride, and lead acid batteries. As the consumption of lithium-based materials has more than doubled in eight (8) years due to the recent surge in demand for lithium-ion batteries,[40] this guidance

[39] See note 37.
[40] H Bae and Y Kim, *Technologies of lithium recycling from waste lithium ion batteries: a review*, 2021.

document assists to explore further on the circularity potential for rechargeable lithium-ion batteries (LiB).

LiB comes in a wide variety of designs, each with unique features as below:[41]

- Lithium cobalt oxide batteries: The most typical kind of LiB, found in a wide range of gadgets, including electric cars, computers, and telephones.
- Lithium manganese oxide batteries: Compared to lithium cobalt oxide batteries, these are less expensive and less potent. When large discharge rates are not necessary, they are employed.
- Phosphate batteries: Of all lithium-ion batteries, these ones have the maximum energy density. They are utilized in electric vehicles and other high-power gadgets as a result.
- Cobalt batteries: Compared to lithium-ion and lithium cobalt oxide batteries, these batteries last longer. They are utilized in drones, electric vehicles, and other gadgets where a longer lifespan is desired.

Nonetheless, the general components of LiB are summarized in **Table 4-2**.

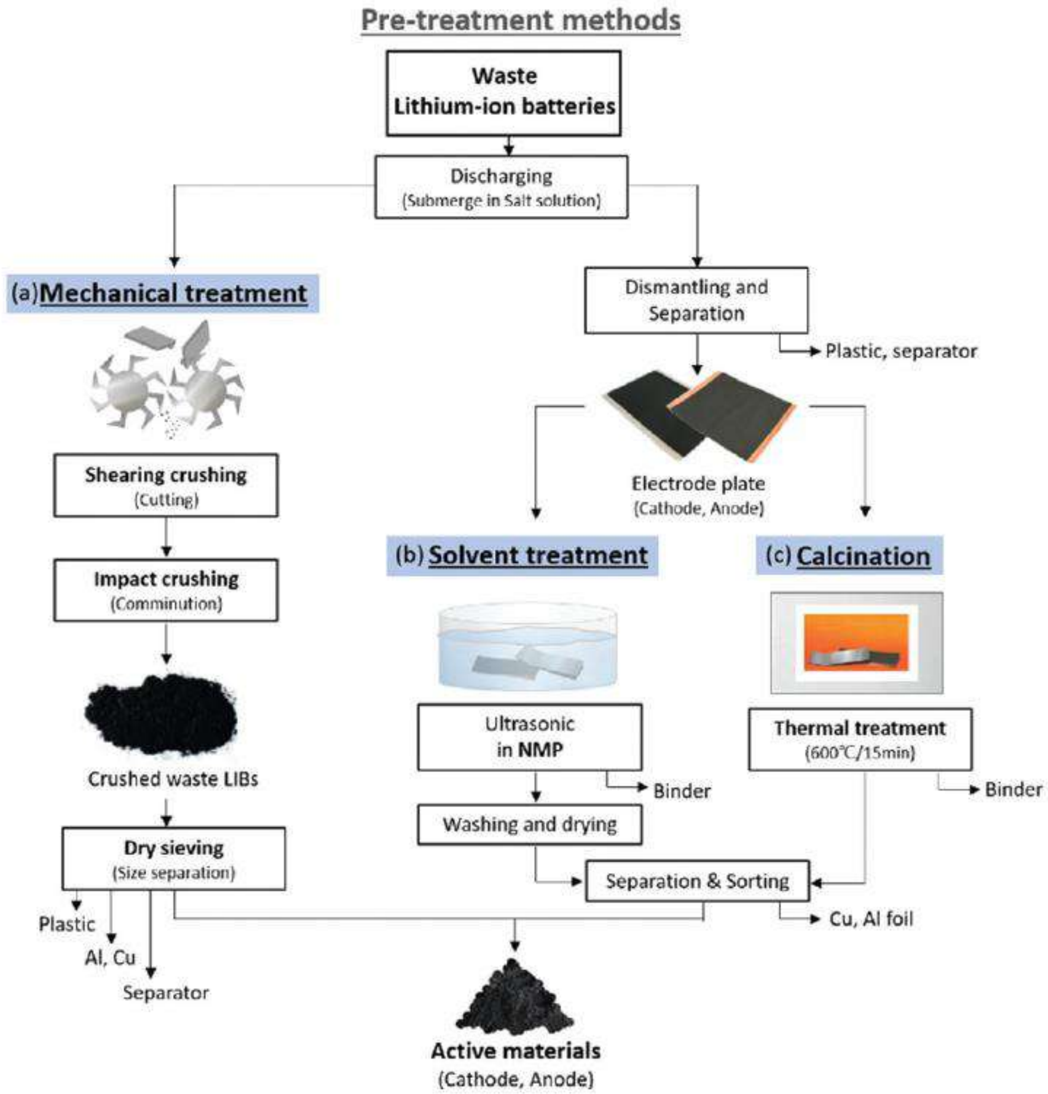
Table 4-2: Common Component of Lithium Batteries[42, 43]

Battery Component	Mass Fraction	Metal Component
Cathode	~7 to 22 wt%	Lithium metal oxides or phosphates in polyvinylidene fluoride (PVDF) binder; $LiCoO_2$ (LCO); $LiFePO_4$ (LFP); $LiMn_2O_4$ (LMO); $LiNi_xCo_yAl_zO_2$ (NCA); $LiNi_{0.3}Mn_{0.3}Co_{0.3}O_2$ (NCM)
Anode	~15 to 17 wt%	Graphite or Si/C composite in PVDF binder
Electrolyte	~10 to 15 wt%	Lithium salts in organic carbonate solvents: lithium hexafluorophosphate ($LiPF_6$) dissolved in dimethyl carbonate (DMC); lithium bis(fluorosulphonyl)imide (LiFSI); lithium 4,5-dicyano-2-trifluoromethyl-imidazolide (LiTDI)
Separator	~4 to 10 wt%	Polyolefins; polypropylene (PP); polyethylene (PE)
Current collectors	~13 to 18 wt%	Aluminium, copper
Casing	~10 to 26 wt%	Steel or aluminium

Prior to the extraction of heavy metals from waste LiB, the waste batteries usually undergo pre-treatment first. Pre-treatments of LiB include mechanical treatment, solvent treatment and calcination, to separate other heavy metals (such as aluminium and copper), plastics, and active material (cathode and anode) (**Figure 4-2**).

41 S S Gadipudi, *Recycling of Lithium-ion Batteries*, 2022.
42 See note 40.
43 Z Baum *et al.*, *Lithium-ion Battery Recycling – Overview of Techniques and Trends*, 2022.

Figure 4-2: Pre-Treatment Methods for Waste Lithium Batteries[44]



Waste of LiB can be recycled or re-processed for extraction of heavy metals such as cobalt (Co) or lithium (Li). Co is the most expensive material in a lithium-ion battery, while Li is an irreplaceable key component in LiB, which used in the cathode, electrolyte, and anode.[45]

4.2.2.1 Reuse Applications

There are no reuse applications for SW 103 under the reuse category as defined in **Chapter 3.3, Table 3-1**.

[44] See note 40.
[45] See note 40.

4.2.2.2 Recovery Technologies

Recovery technologies for LiB comprise mainly of chemical recovery methods, where lithium is extracted via electrochemical methods, precipitation, selective adsorption or even solvent extraction. Apart from chemical recovery methods, lithium and cobalt can also be extracted biologically using acidophilic bacterial strains. Other more comprehensive technologies include the Lithorec II process, which involves physical, thermal and chemical methods, and pyrometallurgy, which utilizes both thermal and chemical methods.

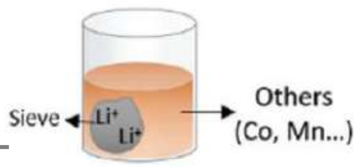
A summary of the recovery technologies for waste LiB are presented in **Table 4-3**, whereas the details of each technology, including the process description, advantages, limitations, recommendations, Waste Acceptance Criteria (WAC), current application of the said technology and Technology Readiness Levels (TRLs) are presented in the next few pages.

Table 4-3: Summary of Recovery Technologies for SW 103 (Waste LiB)

Recovery Technologies	Method	Technology Readiness Level (TRL)	Reference Page
Lithium extraction via selective adsorption	Chemical	4 *Technology validated in lab*	4-11
Metal bioleaching using acidophilic bacterial strains	Biological	4 *Technology validated in lab*	4-12
Lithorec II process	Physical, Thermal and Chemical	6 *Technology demonstrated in relevant environment*	4-13
Electrochemical extraction of lithium	Chemical	9 *Actual system proven in operational environment*	4-14
Lithium extraction via precipitation	Chemical	9 *Actual system proven in operational environment*	4-15
Lithium extraction via solvent extraction	Chemical	9 *Actual system proven in operational environment*	4-16
Pyrometallurgy	Thermal and Chemical	9 *Actual system proven in operational environment*	4-17

LITHIUM EXTRACTION VIA SELECTIVE ADSORPTION[46]

Recovery (Chemical)



Process Description

Active Materials (Cathode containing $LiNi_xMn_yCo_zO_2$ & Anode containing Li_xC_6)

↓

Leaching[46] (in acid, alkali)

↓

Li ion Sieve (MnO_2) → **Li Adsorption[47]** → Other ions (Co^{3+}, Mn^{3+}, Ni^{3+})

↓ Adsorbed Li^+

Acid → **Sieve Acid Leaching[48]**

↓

Precipitant (Na_2CO_3) → **Li Precipitation** → Lithium Chemical (Li_2CO_3)

Advantages

- Simple method.
- Allows for low contamination.
- Guarantees high recovery rates.

Limitations

- Spinel-structured manganese-type lithium-ion sieves are very costly and require an additional leaching process to separate the lithium combined with MnO_2.
- Method requires high volume of acid and base for leaching, which can incur additional chemical costs.
- Backend costs of disposing the used solutions can be high.

WAC

- Pre-sorted and pre-treated waste batteries

Recommendations/ Further Research Required

- Further research is required before it can be scaled up for commercialization.

Current Application

- Laboratory-scale study

T R L 4

Technology validated in lab

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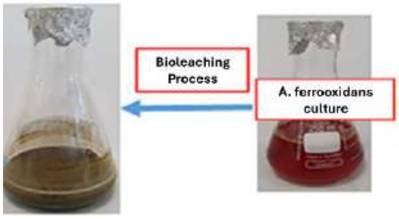
46 See note 40.
47 Selective adsorption separates lithium using a lithium-ion sieve to absorb the dissolved lithium.
48 Lithium-ion sieves are inorganic adsorbents that are extremely selective for lithium in a lithium-containing solution.

METAL BIOLEACHING USING ACIDOPHILIC BACTERIAL STRAINS[49, 50, 51]



Recovery (Biological)

Process Description

Cathode Powder[52]

Waste-Adapted Acidophilic Bacteria[53] (*Acidithiobacillus ferrooxidans* and *Acidithiobacillus thiooxidans*)

Bioleaching

Li and Co

WAC

- Pre-sorted and pre-treated waste batteries

Current Application

- Laboratory-scale study

Advantages

- One of the most promising and fast developing technologies.
- Eco-friendly and effective way of recovering metals.

Limitations

- Higher solid/liquid ratios of battery wastes prevented bacterial activity in the process as higher metal concentrations are considered to be toxic for acidophilic bacteria cells.

Recommendations/ Further Research Required

- Application of bioleaching approach to other battery types to reduce the time of bioleaching and scale up the process.
- Regeneration of cathode and anode materials from bioleaching solution and residue.

TRL 4

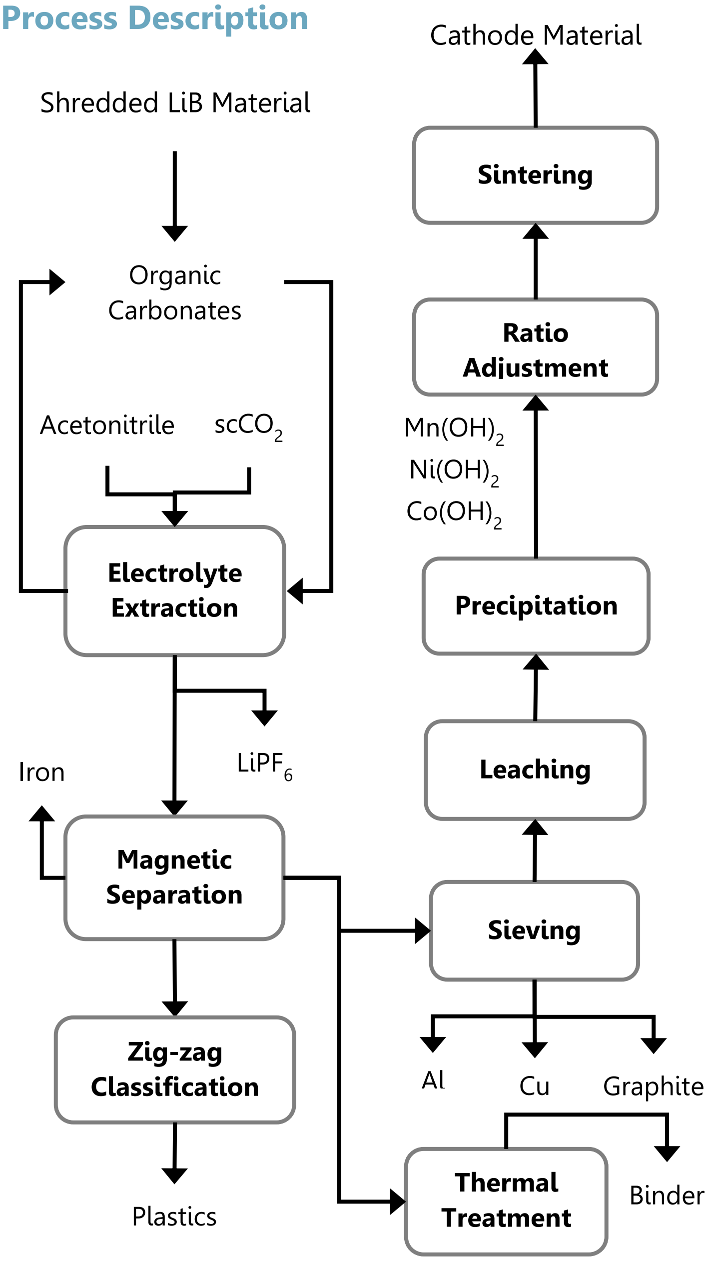
Technology validated in lab

[49] J J Roy, M Srinivasan and B Cao, *Bioleaching as an Eco-Friendly Approach for Metal Recovery from Spent NMC-Based Lithium-Ion Batteries at a High Pulp Density*, 2021.
[50] D Mishra *et al.*, *Bioleaching of metals from spent lithium ion secondary batteries using Acidithiobacillus ferrooxidans*, 2007.
[51] R Marcinčáková *et al.*, *Metal bioleaching from spent lithium-ion batteries using acidophilic bacterial strains*, 2016.
[52] The LIBs were manually cut up into different portions; anode and cathode were uncurled manually, separated and dried for 24h at 60°C.
[53] The mixed bacterial strains were cultured in the rich nutrient medium composed of K_2HPO_4 – 0.1 g, $(NH_4)_2SO_4$ – 2.0 g, KCl – 0.1 g, $MgSO_4.7H_2O$ – 4.0 g, $FeSO_4.7H_2O$ – 44.2 g, elemental sulphur – 4 g/l, and 1000 ml distilled water at the initial pH of 1.5.

LITHOREC II PROCESS[54, 55]

Recovery (Physical, Thermal & Chemical)

Process Description



WAC

- Pre-sorted and pre-treated waste batteries

Current Application

- Temporary demonstration plant was set up in Braunschweig

Advantages

- More holistic recycling process that includes the recovery of the electrolyte.
- The extraction is fast, highly selective and efficient.
- Pre- or post-concentration or cleanup steps are not necessary.

Limitations

- High ecological impact.
- Process is only economically feasible at high throughputs and very sensitive to the market for electric driving systems.

Recommendations/ Further Research Required

- Two main factors, i.e., the future amount of spent battery systems and achievable prices for recycling products, need to be further studied before realizing a pilot plant in the projected scale.

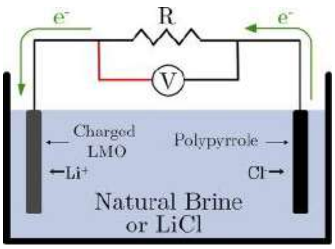
TRL 6

Technology demonstrated in relevant environment

[54] Diekmann *et al.*, *2-The LithoRec Process*, 2018, 35-37.
[55] S Nowak and M Winter, *The Role of Sub- and Supercritical CO_2 as "Processing Solvent" for the Recycling and Sample Preparation of Lithium Ion Battery Electrolytes*, 2017.

ELECTROCHEMICAL EXTRACTION OF LITHIUM[56]

Recovery (Chemical)



Process Description

Active Materials (Cathode containing $LiNi_xMn_yCo_zO_2$ & Anode containing Li_xC_6)

↓

Water → **Waste Solution[57]** (in water)

↓

Electrochemical Extraction[58]

↓

Lithium Chemical[59] (Li_2CO_3) | Other ions (Co^{3+}, Mn^{3+}, Ni^{3+})

WAC

- Pre-sorted and pre-treated waste batteries

Current Application

- Practiced by local industry player

Advantages

- Can also extract lithium metal, if necessary.
- This method only requires charging and discharging and does not require additional chemical compounds or an increase in temperature.
- Lithium-ion batteries can be recycled in an environment-friendly manner using only water.

Limitations

- Requires the setting up of an electrochemical system and solid electrolyte and has only been proven on a laboratory scale.

Recommendations/ Further Research Required

- Further research is required before it can be scaled up for commercialization.

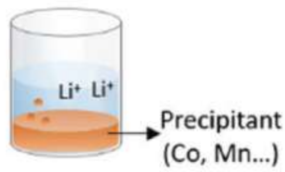
T R L 9

Actual system proven in operational environment

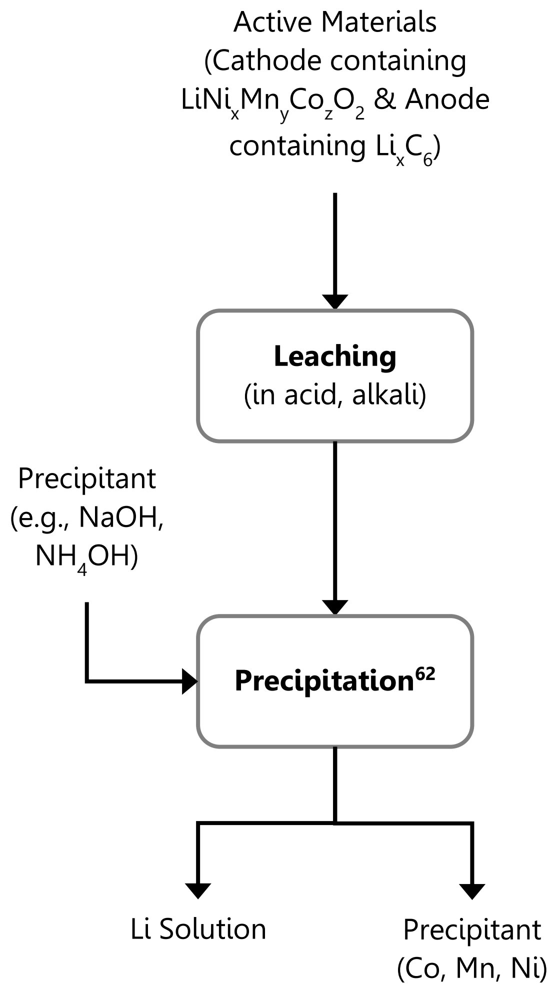
[56] See note 40.
[57] Electrochemical extraction methods separate lithium from pre-treated active materials by putting the active material powder from the pre-treated waste lithium-ion battery in water and separating the lithium using Li-on conductive ceramic solid electrolyte.
[58] During charging, Li separation happens through solid electrolyte, and Li forms at the anode.
[59] After charging, the separated Li^+ is discharged to water, passes through another ceramic solid electrolyte, and undergoes an oxygen reduction reaction (ORR) with water and electrons to form an aqueous LiOH solution, which reacts with CO_2 to form Li_2CO.

LITHIUM EXTRACTION VIA PRECIPITATION[60, 61]

Recovery (Chemical)



Process Description



WAC

- Pre-sorted and pre-treated waste batteries

Current Application

- Practiced by industry player overseas, e.g., TOXCO

Advantages

- Most used method for separating lithium from leached solutions.
- This method is the safest, most economical, and most efficient (retrieval efficiency) among hydrometallurgy methods.

Limitations

- Some cathodes are difficult to leach, so crystal structure needs to be destroyed via calcination or chemical treatment before leaching.

Recommendations/ Further Research Required

- Fine control of the operating conditions (pH, Li concentration, and temperature) is needed to produce the required property profile.

T R L 9

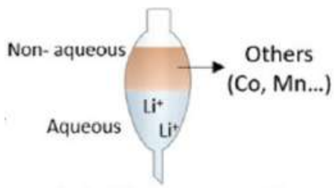
Actual system proven in operational environment

---

[60] See note 40.
[61] E Blumbergs *et al.*, *Cadmium Recovery from Spent Ni-Cd Batteries*, 2021.
[62] Precipitants such as NaOH, Na_3PO_4, and Na_2CO_3 are mainly used to precipitate other dissolved metals, followed by lithium extraction in the form of Li_2CO_3 or Li_3PO_4 by reacting Li^+ and precipitants.

LITHIUM EXTRACTION VIA SOLVENT EXTRACTION[63, 64]

Recovery (Chemical)



Process Description

Active Materials (Cathode containing $LiNi_xMn_yCo_zO_2$ & Anode containing Li_xC_6)

↓

Leaching (in acid, alkali)

↓

Extractant[65] (Cyanex272, PC-88a, D2EHPA) →

Solution Separation[66]

→ Non-aqueous Solution (Co^{3+}, Mn^{3+}, Ni^{3+})

↓ Aqueous Solution (Li^+)

Li Precipitation

↓

Lithium Chemical (Li_2CO_3)

Advantages

- Shorter process than precipitation.

Limitations

- Requires additional extractant chemicals such as Cyanex272 and PC-88A, along with expensive solvents.

WAC

- Pre-sorted and pre-treated waste batteries

Recommendations/ Further Research Required

- Detailed control of the conditions, such as pH and solvent concentration, is needed because the extraction efficiency is greatly affected.

Current Application

- Practiced by local industries, e.g., SungEel HiTech

TRL 9

Actual system proven in operational environment

---

[63] See note 40.
[64] See note 60.
[65] Non-polar extractants are mainly used to separate valuable metals (Co, Ni, Mn) and lithium is separated from stratified solution.
[66] Solvent extraction uses relative solubility to separate ions from polar and non-polar liquids.

PYROMETALLURGY[67, 68, 69]

Recovery (Thermal & Chemical)

Process Description

Active Materials (Cathode containing $LiNi_xMn_yCo_zO_2$ & Anode containing Li_xC_6)

↓

Calcination[70] (> 700˚C)

↓ Heat-treated Product (Li_2CO_3 + Metal oxide)

Water Leaching

↓

Filtration[71]

↓

Water Evaporation → Lithium Chemical[72] (Li_2CO_3)

Advantages

- Method can process large numbers of disposed LiB.
- Process is simple.
- High purity of extracted lithium.

Limitations

- Additional steps are required after calcination, which usually involves dissolving the product in water or solvent and separating it.
- Large amount of solvent is required due to low solubility of Li_2CO_3.
- Requires complicated calcination equipment and can cause emission of harmful gases.

WAC

- Pre-treated active materials in powdered form

Recommendations/ Further Research Required

- Further research is required before implementation.

Current Application

- Practiced by industry players overseas, e.g., INMETCO in USA, ACCUREC in Germany

T R L 9

Actual system proven in operational environment

[67] See note 40.
[68] Climate Policy Watcher, *Cadmium Recovery Inmetco*, 2023.
[69] R Sojka, Q Pan and L Billman, *Comparative study of Li-ion battery recycling processes,* 2020.
[70] At temperatures higher than 700˚C, the lithium metal oxide of the cathode and anode react to form Li_2CO_3 and metal oxides.
[71] After water leaching via filtration, the undissolved metal oxide and the aqueous solution were separated to produce a Li_2CO_3 solution, followed by water evapouration to finally obtain Li_2CO_3.
[72] Some pyrometallurgy uses additional acids for the roasting to increase the lithium extraction efficiency.

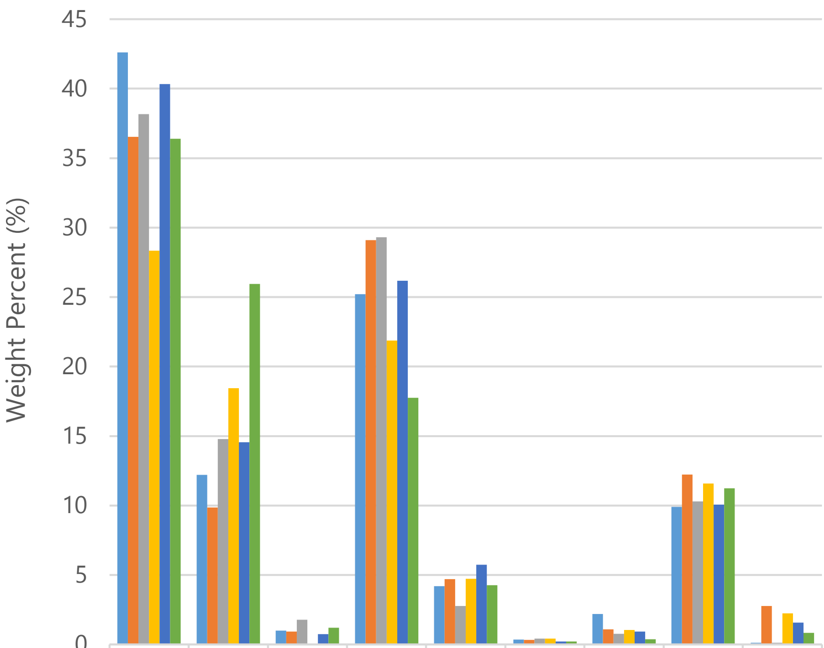
4.2.3 SW 104 – Silico-Manganese Slag from Ferroalloy Industries

Silico-manganese slags are formed in the production of ferroalloy, during the refining process. The composition and physical forms of silico-manganese slag varies from plant to plant based on the production process, whether in feedstock, processing requirements, operating conditions or other conditions.

Chemical Composition

Chemical compositions of some Si-Mn slags from different part of the world are presented in **Figure 4-3**. Typically, Si-Mn slag is silico-calcic in nature where its major oxide components are Silicon dioxide (SiO_2), Calcium oxide (CaO), Aluminium oxide (Al_2O_3), and Manganese oxide (MnO) which have an average wt.% of 37.06, 24.90, 15.96 and 10.88 respectively. Its chemical composition similar to blast furnace slag, except it is more acidic due to higher SiO_2 and lower CaO and also contains ~10 wt.% MnO.

Figure 4-3: Chemical Compositions of Si-Mn Slag (wt%) in Spain, Iran, China and India[73]



	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	MnO	SO_3
Ferroatlantica S. L., Spain	42.6	12.2	1	25.2	4.2	0.36	2.2	9.9	0.12
Ferroatlantica S. L., Spain	36.53	9.86	0.92	29.1	4.69	0.34	1.08	12.23	2.77
Faryab Ferro Alloy Plant, Iran	38.17	14.78	1.79	29.3	2.77	0.42	0.76	10.29	0.12
Miaxian Steel Co., China	28.34	18.45	0	21.86	4.72	0.41	1.04	11.58	2.23
JSP, India	40.33	14.55	0.75	26.17	5.74	0.21	0.92	10.06	1.57
Shyam Ferro Alloy, India	36.4	25.94	1.2	17.74	4.27	0.21	0.37	11.23	0.84

[73] S K Nath, N S Randhawa and S Kumar, *A Review on Characteristics of Silico-Manganese Slag and Its Utilisation Into Construction Materials*, 2022.

Physical Form

The physical appearance or characteristics of slag depends on molten slag tapping and subsequent cooling process as follows:

- Air cooled – Lumpy forms, hard, dense, and crystalline similar to a coarse aggregate of crushed rock due to slow solidification.
- Water quenched – Granulated form (1-4mm), glassy (amorphous), disintegrated into small fragments due to rapid solidification. More reactive than air cooled Si-Mn slag due to the presence of metastable glassy fractions.

4.2.3.1 Reuse Applications

SiMn slag may have the potential to be reused as a backfill material for retaining walls due to its ability to reduce earth pressure and as fill material in reinforced earth structures, owing to its favourable frictional properties[74]. Nevertheless, its ultimate application in this context requires the conducting of leaching studies.

4.2.3.2 Recovery Technologies

Recovery technologies for SiMn slag comprises mainly of physical recovery methods, where the slag is crushed, milled or ground prior to reuse as supplementary material or raw materials in the construction industry. A summary of the recovery technologies for SiMn slag can be referred in **Table 4-4**.

Table 4-4: Summary of Recovery Technologies for SW 104 (SiMn Slag from Ferroalloy Industries)

Recovery Technologies	Method	Technology Readiness Level (TRL)	Reference Page
Used as potential raw material for alkali activated cement binders (AAB)	Physical then Chemical	4 *Technology validated in lab*	4-21
Used for soil amendment	Physical	4 *Technology validated in lab*	4-22
Utilization into an eco-efficient $CaMoO_4$/Electroconductive Geopolymer Composite (EGC)	Chemical	4 *Technology validated in lab*	4-23
Calcination to extract manganese	Thermal	4 *Technology validated in lab*	4-24
Reduction to recover manganese	Chemical	4 *Technology validated in lab*	4-25

[74] K R Kumar, J Lokesh and C N V S Reddy, *Geotechnical Characterization of Silico Manganese Slag for Civil Engineering Applications*, 2013.

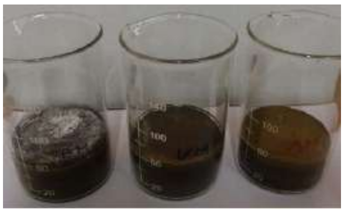
Recovery Technologies	Method	Technology Readiness Level (TRL)	Reference Page
Reused for welding flux manufacturing	Chemical	9 *Actual system proven in operational environment*	4-26
Used as supplementary cementitious material (SCM)	Physical	9 *Actual system proven in operational environment*	4-27
Used as aggregates in concrete	Physical	9 *Actual system proven in operational environment*	4-28
Used as road base and/or sub-base	Physical	9 *Actual system proven in operational environment*	4-29
Magnetic separation to extract manganese	Physical	9 *Actual system proven in operational environment*	4-30
Leaching process to extract manganese	Chemical	9 *Actual system proven in operational environment*	4-31

Even though SiMn slag has been widely explored as supplementary cementitious materials, aggregate and Alkali Activated Cement Binders (AAB), there is still no comprehensive data on the utilization of SiMn slag into building and construction materials.[75] This may be mainly due to the non-comparable research methodology and change of slag nature, curing condition etc., which makes the commercialization of SiMn slag recovery technologies a challenge.

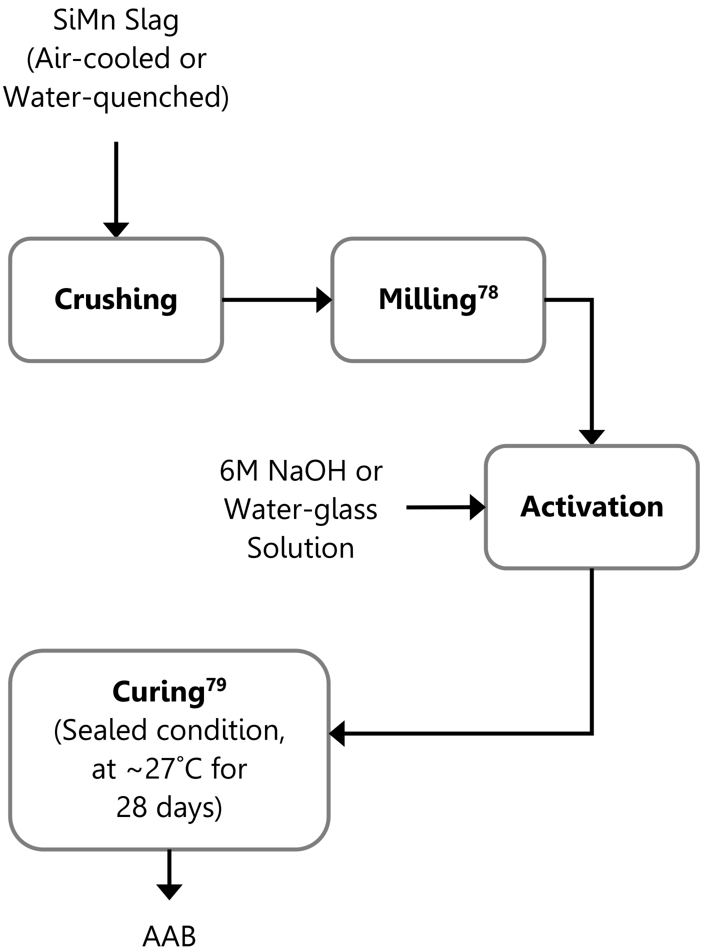
[75] See note 73.

USED AS POTENTIAL RAW MATERIAL FOR ALKALI-ACTIVATED CEMENT BINDERS (AAB)[76, 77]

Recovery (Physical then Chemical)



Process Description



WAC

- Milled SiMn Slag

Current Application

- Laboratory-scale study

Advantages

- Granulated slag gives excellent properties after alkali activation, and resultant products are durable.

Limitations

- Structure becomes spongy with uneven distribution of porosity after alkali interaction.

Recommendations/ Further Research Required

- Leaching study is required before large-scale production and commercial adoption.

TRL 4

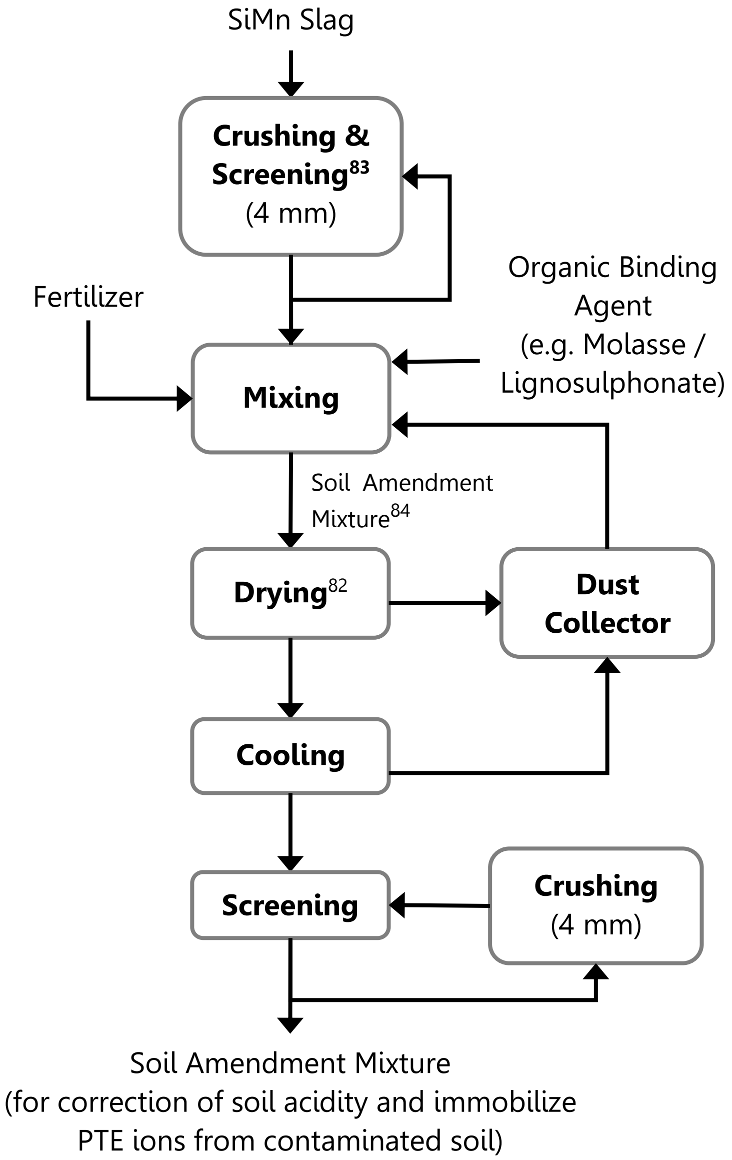
Technology validated in lab

[76] See note 73.
[77] See note 74.
[78] SiMn slag lump will be crushed, then milled to be mechanically activated.
[79] Chemically activated slag via NaOH or water-glass solution can then be cured to form AAB.

USED FOR SOIL AMENDMENT[80, 81, 82]

Recovery (Physical)

Process Description



WAC

- Crushed and screen SiMn Slag at 4 mm size
- Depending on soil composition

Current Application

- Feasibility studies by local industry players
- Laboratory-scale studies by overseas researchers

Advantages

- Disposal of slag wastes can be reduced, and at the same time, make them useful in the acid soils amelioration process.

Limitations

- No fixed optimum weight ratio of soil-slag mixture, as it is dependent on soil pH.

Recommendations/ Further Research Required

- Evaluation of chemical, structural and morphological properties to determine the optimum weight ratio of soil-slag mixture for a balanced soil pH.
- Further studies which consist in eco-toxicity tests of slag-soils mixtures on the adsorption and immobilization of potential toxic elements from soil for sustainable agriculture should be conducted.

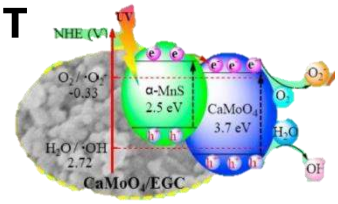
TRL 4

Technology validated in lab

---

80 D L Buruiana *et al., Re-Use of Silico-Manganese Slag*, 2021.
81 Jobes, *The Difference Between a Fertiliser and a Soil Amendment*, 2018.
82 Pertama Ferroalloys, 2023.
83 SiMn slag lump will be crushed and screened then mixed with fertilizer and organic binding agent at an optimum ratio.
84 The soil amendment mixture will then be further dried, cooled and then screened before usage.

UTILIZATION INTO AN ECO-EFFICIENT $CaMoO_4$/ELECTROCONDUCTIVE GEOPOLYMER COMPOSITE (EGC)[85, 86]



Recovery (Chemical)

Process Description

SiMn Slag → **Milling** → **Stirring** (5 mins.) [+ Electroconductive Carbon Black, NaOH] → **Moulding** (80˚C for 6 hours) → **Curing** (Room cond. for 18 hours) → **Curing** (27 days) → Monolith of EGC → **Crushing** → EGC Particles → **Immersing twice in aqueous ammonium acetate solution** (Room temp. for 2 hours) → **Filtration** → **Drying** → NH_4^+-EGC → **Immersing in ammonium molybdate tetrahydrate** (Overnight) → **Calcination** (400˚C for 4 hours) → $CaMoO_4$/EGC (as novel catalyst for treatment of dye wastewater)

Advantages

- High photocatalytic degradation activity and excellent stability compared to commercial catalyst.

Limitations

- Long processing time required.

Recommendations/ Further Research Required

- Needs more effort in studying the application and development.

WAC

- Milled SiMn Slag

Current Application

- Laboratory-scale study

TRL 4

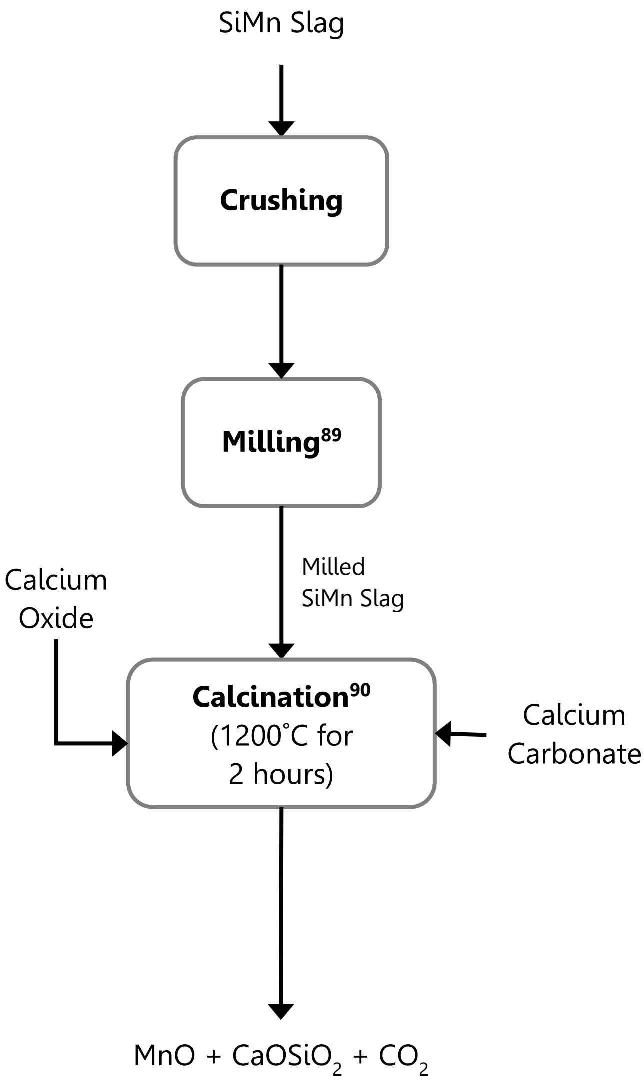
Technology validated in lab

[85] K He *et al., Patent No. CN103198906A*, 2013.
[86] See note 73.

CALCINATION TO EXTRACT MANGANESE[87, 88]

Recovery (Thermal)

Process Description



WAC

- Crushed and milled SiMn Slag

Current Application

- Laboratory-scale study

Advantages

- Method is in concordance with the sustainable use of natural resources for the achievement of sustainable development.
- Remaining fraction of the slag can be used as aggregate sources.

Limitations

- Method is expensive in extracting manganese from SiMn slag.

Recommendations/ Further Research Required

- Evolution of slag dump should be further monitored and leaching process should be improved in future studies.
- Different ways to extract manganese from leaching solution and introduction into the metallurgical process should be studied.

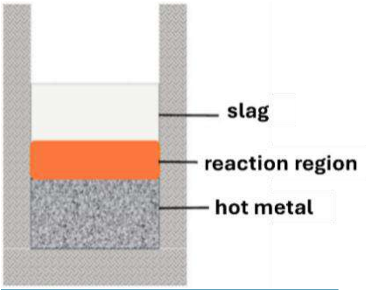
TRL 4

Technology validated in lab

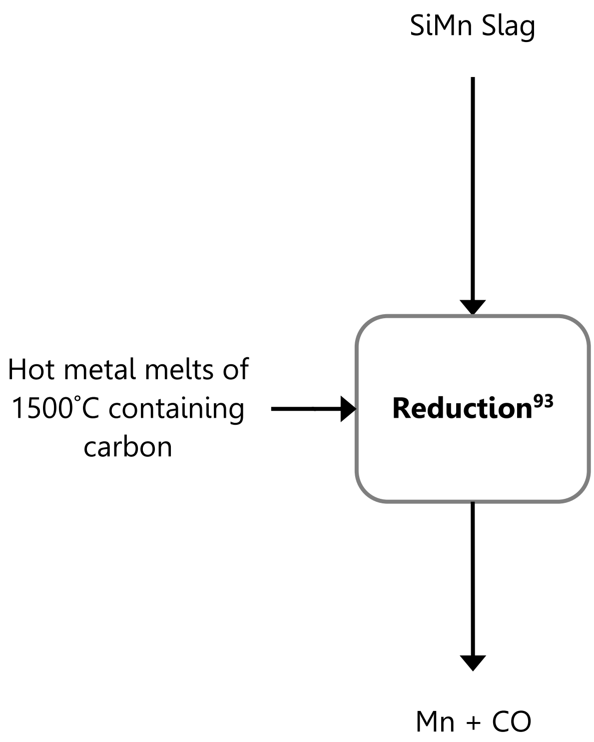
[87] See note 80.
[88] Process Heating, *High Temperature Processing Using Indirectly Heated Rotary Calciners*, 2014.
[89] SiMn slag lump will be crushed and milled into smaller size fractions.
[90] Powdered SiMn slag will be mixed with calcium oxide and calcium carbonate, then calcinated at 1200˚C for 2 hours.

REDUCTION TO RECOVER MANGANESE[91, 92]

Recovery (Chemical)



Process Description



Advantages

- Degree of manganese extraction may be increased by using tailings slag to alloy hot metal with manganese.

Limitations

- Reduction in the presence of metallic melt that contains sufficient quantities of elements whose oxygen affinity exceeds that of manganese, such as hot metal.

Recommendations/ Further Research Required

- Required to establish thermodynamic analysis.

WAC

- Not specified

Current Application

- Laboratory-scale study

T R L 4

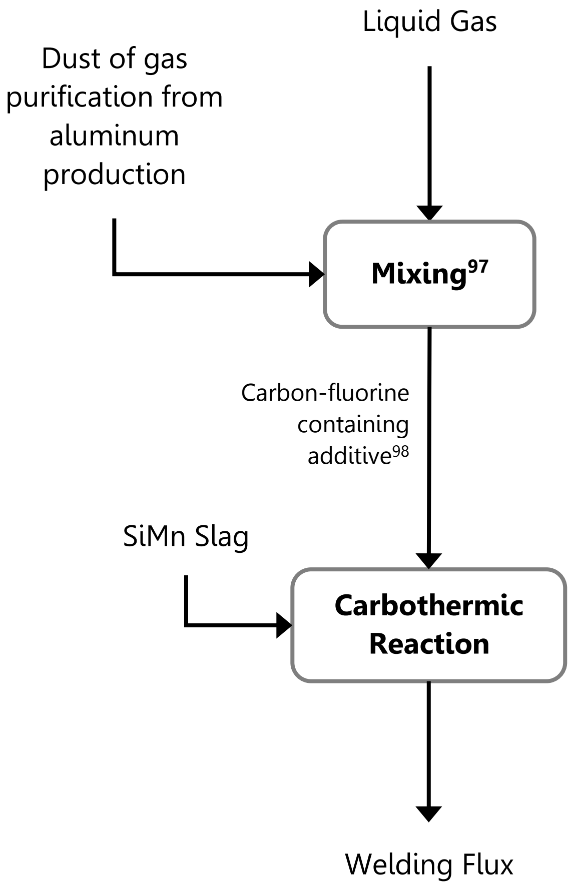
Technology validated in lab

[91] A A Aleksandrov, V Y Dashevskii and L I Leont'ev, *Manganese extraction from slag obtained in the production of refined manganese ferroalloys*, 2013.
[92] Y Guo *et al.*, *Desulphurisation Ability of Blast Furnace Slag Containing High Al2O3 at 1773 K*, 2021.
[93] SiMn slag reacts with hot metal melts of 1500˚C containing carbon, where reduction of manganese occurs.

REUSED FOR WELDING FLUX MANUFACTURING[94, 95, 96]

Recovery (Chemical)

Process Description



Advantages

- Reduce costs of welding fluxes by utilizing slag waste generated from ferroalloy production.

Limitations

- Requires the introduction of carbon-fluorine containing additive into the flux to improve the performance of weld.

Recommendations/ Further Research Required

- More studies should be conducted to improve the welding flux's value of impact strength at negative temperatures.

WAC

- Not specified

Current Application

- Fused fluxes (using materials other than SiMn slags) produced in Ukraine is widely used in welding and surfacing of low-alloyed steels in Russia
- Practiced by local industry players

TRL 9

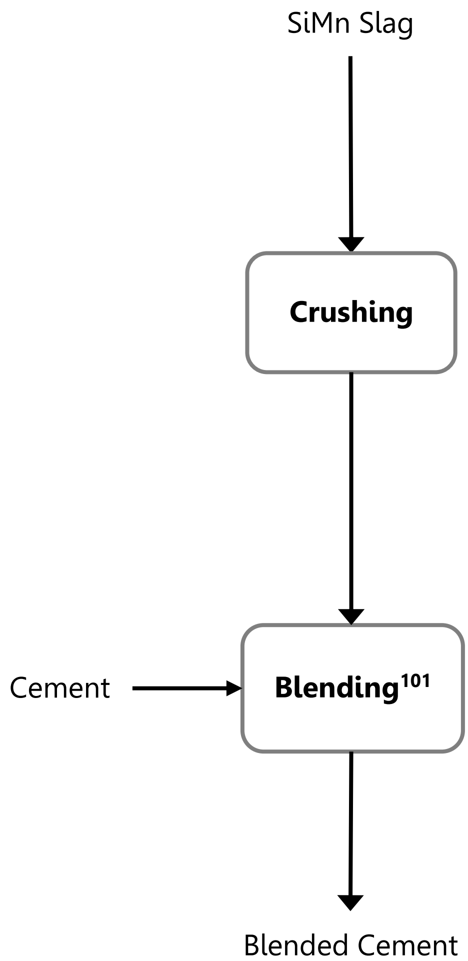
Technology validated in relevant environment

[94] Kozyrev *et al.*, *On the use of slag from silicomanganese production for welding flux manufacturing*, 2015.
[95] TWI Global, *What is Flux-Cored Arc Welding (FCAW AKA Dual Shield Welding)*, 2023.
[96] This technology is according to the protected patents of the Russian Federation.
[97] Dust of gas purification from aluminum production will be mixed with liquid glass and used for manufacturing of carbon-fluorine containing additive PD-UVC.
[98] This additive will be used in the continuous carbothermic method of the SiMn slag to form welding flux.

USED AS SUPPLEMENTARY CEMENTITIOUS MATERIAL (SCM)[99, 100]

Recovery (Physical)

Process Description



WAC

- Low MnO (<15%) granulated

Current Application

- Practiced by local industry players

Advantages

- SiMn slag recovery and reuse as supplementary cementitious materials help to lower CO_2 emission, reduce energy consumption and production increment without requiring new heating facility.

Limitations

- Inconsistency in quality of SiMn slag makes it difficult in having a fixed blending mix/ratio.

Recommendations/ Further Research Required

- More comprehensive data on utilization of silico-manganese slag into building and construction materials are required.
- Leaching study is required before any large-scale production and commercial adoption.

TRL 9

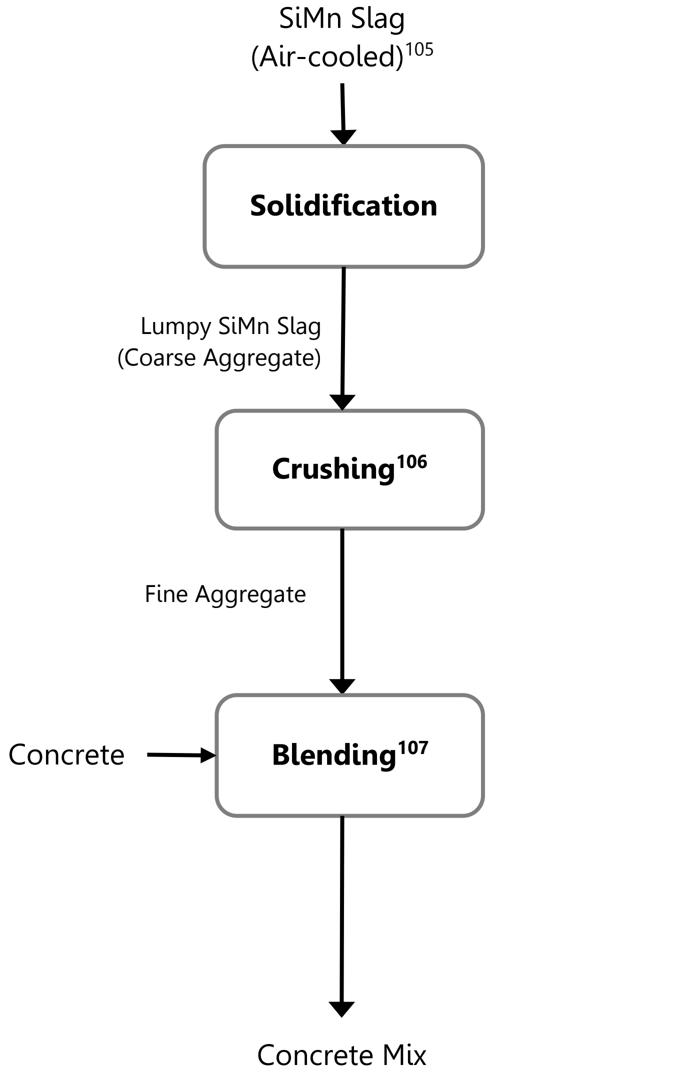
Actual system proven in operation environment

[99] Concrete NZ, *Supplementary Cementitious Material (SCM) Research*, undated.
[100] See note 73.
[101] SiMn slag can be blended using high-speed mixer with cement due to its pozzolanic characteristics.

USED AS AGGREGATES IN CONCRETE[102, 103, 104]

Recovery (Physical)

Process Description



WAC

- Air-cooled molten slag

Current Application

- Practiced by local industry players

Advantages

- More environmentally friendly substitute for river-dredged sand.
- May possess better strength properties.
- Can be used when maximum durability, higher strength, hardness of aggregate, fire resistance, better insulation, and lighter weight are required.

Limitations

- Current investigations on usage are carried out in a scattered manner and confined with limited amount of sample preparation, testing and characterizations.
- Density and absorption of SiMn slag may be different from most conventional concrete aggregates.

Recommendations/ Further Research Required

- Leaching study is required to be included before any structural application.
- Large number sample preparation, durability study in different environments, performance mapping and techno-economics have to be further studied.

T R L 9

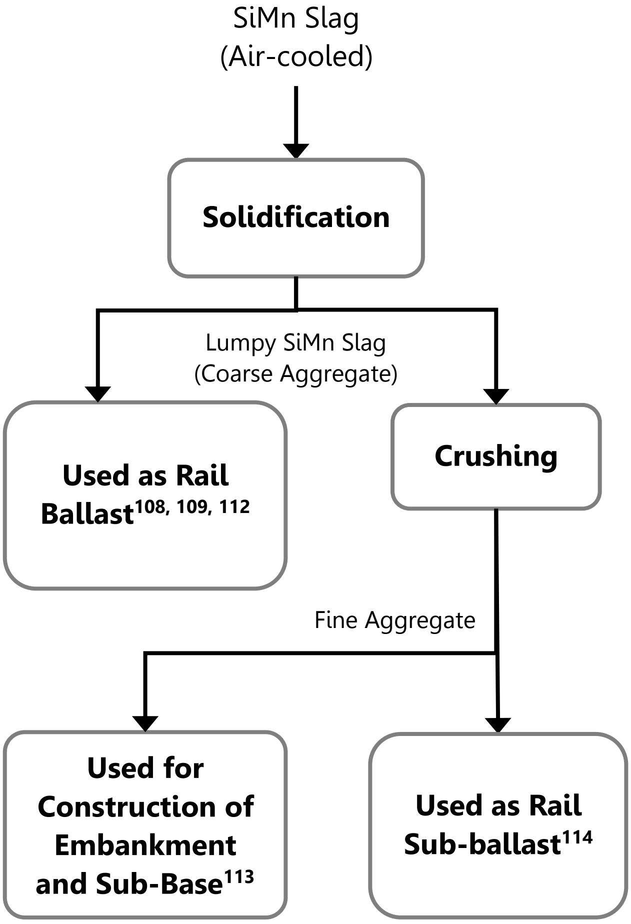
Actual system proven in operation environment

102 V Montjoy, *What is Steel Slag Concrete*, 2023.
103 See note 73.
104 A V Patil and A M Pande, *Behaviour of Silico Manganese Slag Manufactured Aggregate as Material for Road and Rail Track Construction*, 2011.
105 Air-cooled molten slag will be solidified into lumpy form.
106 Lumpy SiMn slag can be further crushed to form fine aggregates which can be blended into concrete.
107 Some oxide contents, such as CaO, MgO, SiO_2 can be interacted with produced cement gel and improves the performance of the concrete.

USED AS ROAD BASE AND/ OR SUB-BASE[108, 109, 110, 111]

Recovery (Physical)

Process Description



WAC

- Not specified

Current Application

- Practiced by local industry players, e.g., OM Materials and Pertama Ferroalloys
- Practiced by industry players overseas, e.g., Dongbu Metal Company in Korea

Advantages

- SiMn slags are highly resistant to change by wetting and drying, freezing and thawing, extreme changes in temperature and chemical attacks.

Limitations

- SiMn slag aggregates are not in a definite shape and texture and have sharp edges; hence, may not be suitable to make a smooth finish on surface.

Recommendations/ Further Research Required

- Leaching study should be conducted before any structural application.

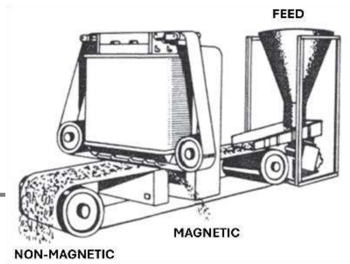
TRL 9

Actual system proven in operation environment

[108] Agico Group, *Why Are There Crushed Stones Alongside Rail Tracks*, 2023.
[109] OM Materials, 2023.
[110] See note 104.
[111] See note 82.
[112] For all types of railroad tracks, from industrial sidings to high-speed main lines.
[113] Used as structural fill material.
[114] Used to prevent intrusion of sub-grade soils into the ballast sections.

MAGNETIC SEPARATION TO EXTRACT MANGANESE[115]

Recovery (Physical)



Process Description

SiMn Slag

Crushing[116]

Pulverizing

Sieving[117]

SiMn Powder

-500 ~ +280μm

-280 ~ +200μm

-200 ~ +150μm

-150 ~ 75μm

Magnetic Separation[118]
(6,000 Tesla)

Magnetic particles (containing Mn-rich particles)

Non-magnetic particles (containing Mn-poor particles)

Advantages

- Simple operation and maintenance.

Limitations

- Percentage recovery of manganese may not be very high depending on the contents (mass%) of Mn in slag.
- Difficult to measure experimentally the magnetic strength for each particle.

Recommendations/ Further Research Required

- Further research is required before implementation.

T R L 9

Actual system proven in operation environment

WAC

- Manganese-rich slag containing over 20mass% manganese

Current Application

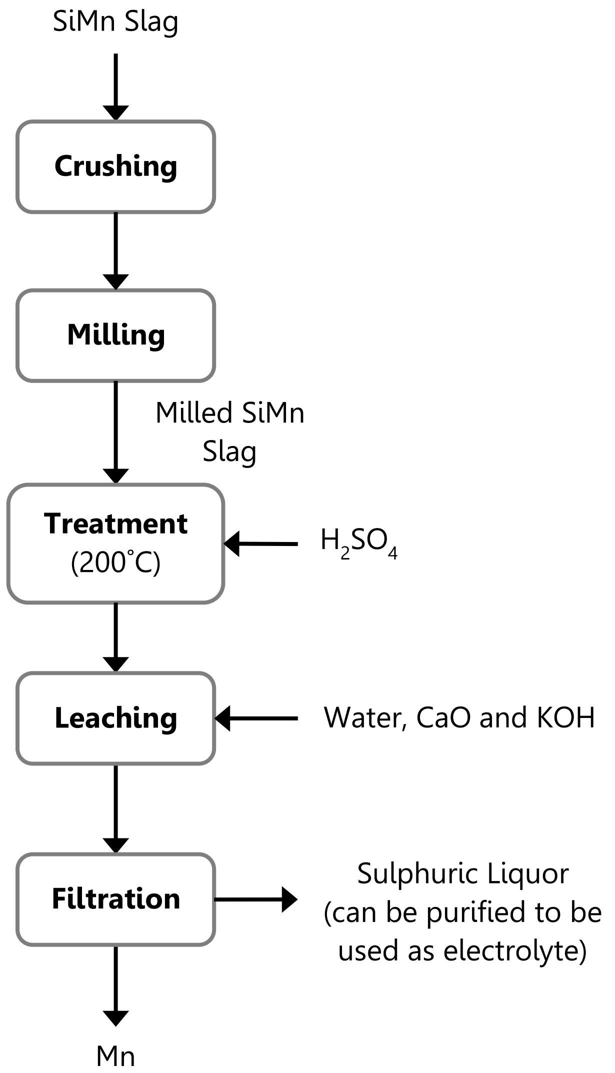
- Laboratory-scale study by Dongbu Metal Company in Korea
- Technology has been commonly practiced

[115] B S Kim *et al.*, *Upgrading of Manganese from Waste Silicomanganese Slag by a Mechanical Separation Process*, 2011.
[116] SiMn slag will be crushed and pulverized into smaller particle sized powder (ranging under 500μm)
[117] The powder will then be sieved to four sizes, +280μm, +200μm, +150μm, +75μm.
[118] Dry magnetic separation will then be conducted at a magnetic field of about 6,000 Tesla for each of the particle sizes.

LEACHING PROCESS TO EXTRACT MANGANESE[119, 120, 121, 122]

Recovery (Chemical)

Process Description



Advantages

- High recovery rate.
- H_2SO_4 has lower cost compared to other acids, and sulphate solution is less corrosive.

Limitations

- Favourable only for high concentration of recoverable metals in slag.

Recommendations/ Further Research Required

- Development of more efficient and environmentally-friendly methods for metal dissolution from industrial sludges contaminated with multiple metals, while increasing selectivity and energy use efficiency in the concentration and purification and recovery steps.

WAC

- Crushed and milled slag

Current Application

- Practiced by industry players

TRL 9

Actual system proven in operation environment

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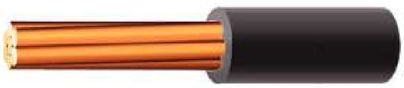
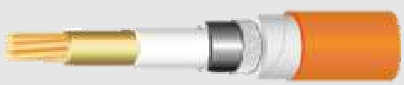
[119] J Ayala and B Fernandez, *Recovery of manganese from silicomanganese slag by means of a hydrometallurgical process*, 2015.
[120] V Gunarathne *et al.*, *Hydrometallurgical processes for heavy metals recovery from industrial sludges*, 2020
[121] A Habib, H N Bhatti and M Iqbal, *Metallurgical Processing Strategies for Metals Recovery from Industrial Slags*, 2019.
[122] Metso, *Leaching Process: Ensuring optimal recovery*, 2023.

4.2.4 SW 110 – Spent Insulated Copper Wire and Cable

A wire is a single conductor contained within the jacket, whereas a cable is composed of several components: a group of electric conductors, which is a conductive metal core, insulation, auxiliary elements (which ensures the cable's protection and longevity), and an outer sheath that covers and protects all of these materials).[123] Selected cable types, their composition and approximate weights are summarized in **Table 4-5**.

Table 4-5: Composition and Weights of Selected Cable Types[124]

Cable Type	Composition	Approximate Weight (kg/km)
PHELPS DODGE Cable Type 60227 IEC 01 	• Annealed copper • PVC insulation	21 – 3,987
PHELPS DODGE Cable Type 60227 IEC 10 	• Annealed copper • PVC insulation • PVC inner sheath • PVC outer sheath	115 – 1,256
Medium Voltage Cross-Linked Polyethylene Cable (XLPE) 	• Conductor • Conductor shield • Insulation • Insulation shield • Metallic shield • Filler • Binding tape • Oversheath • Insulation: XLPE	1,705 – 13,010
0.6/1(1.2) kV Fire Resistant Low Smoke and Halogen Free Cable 	• Conductor • Fire barrier (mica tape) • Insulation • Inner sheath • Armour • Binding tape • Outer sheath	274 – 8,440
PHELPS DODGE Cable Type CV-AWA 	• Conductor • Cross-linked PE (XLPE) insulation • PVC inner sheath • Aluminium wire armour • Binding tape • PVC sheath	136 – 7,344

[123] L Blinová and P Godovčin, *Importance of Recycling the Waste-Cables Containing Copper and PVC*, 2021.
[124] ibid.

Cable Type	Composition	Approximate Weight (kg/km)
AL-PE Sheathed Cable 	• PE or PP insulated conductor • Non-hygroscopic tape • Aluminium shield • PE sheath • Support messenger	250 – 1,720

The insulation layers can be categorized into two (2) groups: thermoplastics (e.g. polyvinyl chloride or PVC, polyolefins, linear polyethylene, polyurethane etc.) and thermosets (e.g. ethylene propylene, crosslinked polyethylene or XLPE, ethyl vinyl acetate, silicone, neoprene, natural rubber etc.).[125] The types of insulation layers and their respective descriptions are summarized in **Table 4-6**.

Table 4-6: Types of Insulation Layers[126]

Type of Insulation Layers	Description
Thermoplastics	
Chlorinated Polyethylene (CPE)	• Available in both thermoplastic and thermoset (cross-linked) versions • Thermoplastic CPE is more common than thermoset CPE
Polyvinyl Chloride (PVC)	• Does not usually exhibit extremely high- and low-temperature properties in one formulation • Many varieties of PVC, which also differs in pliability and electrical properties • Typical dielectric constant values range from 3.5 to 6.5 • Ability to resist oils, acids, alkalis, sunlight, heat, weathering and abrasion when properly formulated
Fluoropolymers	• Extrudable thermoplastics, except PTFE Teflon (also known as TFE) • Most commonly used fluoropolymers are Teflon (PTFE, FEP and PFA), Tefzel (ETFE), Halar (ECTFE) and Kynar or Solef (PVDF) • Contain fluorine in their molecular composition, which contributes to their excellent thermal, chemical, mechanical and electrical characteristics
Polyethylene (PE)	• Has excellent electrical properties • Has low dielectric constant, a stable dielectric constant over a wide frequency range, and very high insulation resistance • Stiff and very hard, depending on molecular weight and density • Excellent moisture resistance • Excellent weather resistance if properly formulated

[125] See note 123.
[126] Anixter, *Technical Information Handbook Wire and Cable*, 2013, 38-42.

Type of Insulation Layers	Description
Polypropylene (PP)	• Similar in electrical properties to polyethylene • Harder than polyethylene
Thermoplastic Elastomer (TPE) or Thermoplastic Rubber (TPR)	• Excellent cold temperature characteristics • Resistant to aging from sunlight, oxidation and atmospheric ozone • Retains most of its physical and electrical properties in the face of many severe environmental conditions such as a salt water environment • Good chemical resistance to all substances except hydrocarbons • Good abrasion resistance, resistance to wear, cut and impact
Polyurethane (PUR)	• Has excellent oxidation, oil and ozone resistance • Some formulations also have good flame resistance • Excellent abrasion resistance • Outstanding "memory" properties, making it an ideal jacket material for retractile cords
Thermosets	
Chlorinated Polyethylene (CPE)	• Outstanding physical and electrical properties for many cable jacket applications • Highly resistant to cold flow (compression set) and other forms of external loading as well as heat, light and chemical attack • Resistant to ozone and ultraviolet (sunlight) degradation • Will withstand prolonged immersion in water when properly compounded • Excellent low temperature impact resistance • Will maintain adequate flexibility after repeated aging at elevated temperatures • Known for abrasion resistance and long life in mining cable applications • Does not support the growth of mould, mildew or fungus • Resistant to most strong acids and bases and many solvents except for chlorinated organics • Good resistance to oils and fuels • Can be conveniently coloured over a wide range and will maintain colour upon aging

Type of Insulation Layers	Description
Neoprene (CP) or Chloroprene	• Vulcanized synthetic rubber • Provides a resilient jacket that resists permanent deformation under heat and load, and does not embrittle at low temperatures • Highly resistant to aging from sunlight and oxidation, and is virtually immune to atmospheric ozone • Excellent resistance to soil acids and alkalis • Unable to be deteriorate by mildew, fungus and other biological agents when properly compounded • Tough, strong, resilient and have excellent resistance to abrasive wear, impact, crushing and chipping
Cross-linked Polyethylene (XLP or XLPE)	• Frequently used polymer in wire and cable • Very high insulation resistance, high dielectric strength and low dielectric constant • Very tough material at temperatures below 100°C, so it is resistant to cutting, impact and other mechanical forces • Low-temperature performance is very good • Poor fire resistance unless flame retardants are added
Ethylene Propylene Rubber (EP, EPR or EPDM)	• Common synthetic rubber polymer used as an insulation in electrical wire and cable • Used in many highly flexible cables • Good dielectric strength, but not as high as that of PE or XLPE • Abrasion resistant and is suitable for use at temperatures down to -60°C • Fairly flame retardant • Very good high-temperature characteristics
Hypalon (CSP)	• Thermosetting, cross-linked, chlorosulphonated polyethylene made by DuPont with many excellent physical and electrical properties • Inherently resistant to cold flow (compression set) resulting from clamping pressures and other forms of external loading • Immune to attack by ozone • Highly resistant to aging from sunlight and oxidation • Extremely low water absorption when properly compounded • Highly resistant to attack by hydrocarbon oil and fuels • Provides high resistance to impact, crushing and chipping
Silicone	• Soft, rubbery insulation • Has excellent electrical properties plus ozone resistance, low moisture absorption, weather resistance, and radiation resistance • Typically has low mechanical strength and poor scuff resistance

The chemical composition of wire and cable insulators vary among manufacturers with their strategies to meet or exceed Institute of Electrical and Electronics Engineers (IEEE) qualification specification[127]. Some examples of power cable insulator composition can be referred in **Table 4-7**.

Table 4-7: Examples of Insulated Wire or Cable Insulator Composition[128]

Type of Wire / Cable	Composition
Medium Voltage Ethylene Propylene Diene Rubber Elastomer (EPDM) Power Cable	• Vistalon EPDM 1703P • Translink 37 Calcined Clay • AGERITE MA Antioxidant • Drimix A-172 • Zinc Oxide • Lead Red ERD-90 • Low Density Polyethylene (LDPE) Escorene LD-400 • Paraffin Wax (133F M.P.) • VAROX DCP-40KE Peroxide
Medium Voltage XLPE Power Cable	• LDPE • VAROX DCP Peroxide • Antioxidant

4.2.4.1 Reuse Applications

There are no reuse applications for spent insulated copper wire and cable under the reuse category as defined in **Chapter 3.3, Table 3-1**.

4.2.4.2 Recovery Technologies

Recovery of spent insulated copper wire and cable often comprises of two (2) main processes, namely:

i. Pre-treatment process, which is also commonly known as partial recovery, where the insulator is separated from the wire at this stage; and
ii. Recovery process, where the separated components (insulator and copper core) are converted into alternative raw materials which can be used back into the product manufacturing processes.

Pre-Treatment Technologies

In general, spent insulated copper wires and cables will be separated into plastic insulator and copper core prior to further processing. These separation techniques are mainly physical and does not change the chemical constituents of the spent insulated copper wires and cables (**Table 4-8**).

[127] KL Simmons *et al.*, *Determining Remaining Useful Life of Aging Cables in Nuclear Power Plants – Interim Study FY13*, 2013, 2.1-2.3.
[128] ibid.

Table 4-8: Summary of Pre-Treatment Technologies for SW 110 (Spent Insulated Copper Wire and Cable)

Pre-Treatment Technologies	Method	Technology Readiness Level (TRL)	Reference Page
Selective/Froth flotation	Physical	4 *Technology validated in lab*	4-38
Hot water separation	Physical	4 *Technology validated in lab*	4-39
Ultrasonic separation	Physical	4 *Technology validated in lab*	4-40
High-pressure water jet technology	Physical	4 *Technology validated in lab*	4-41
Cryogenic grinding technology (freezing process)	Physical	8 *System complete and qualified*	4-42
Gravity/Density-based separation	Physical	9 *Actual system proven in operational environment*	4-43
Electrostatic separation	Physical	9 *Actual system proven in operational environment*	4-44

<u>Recovery Technologies</u>

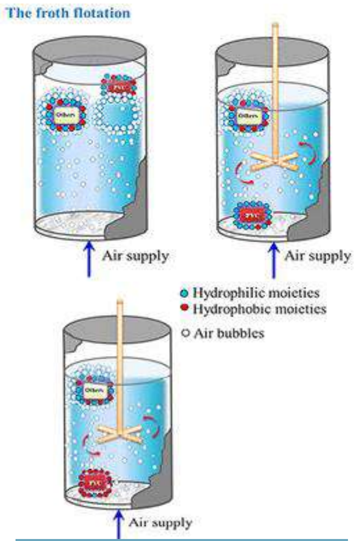
Insulator from spent insulated copper wire and cable is most commonly recovered via the mechanical recycling method (**Table 4-9**).

Table 4-9: Summary of Recovery Technologies for SW 110 (Spent Insulated Copper Wire and Cable)

Recovery Technologies	Method	Technology Readiness Level (TRL)	Reference Page
Pyrolysis	Thermal	4 *Technology validated in lab*	4-45
Mechanical recycling	Physical	9 *Actual system proven in operational environment*	4-46

SELECTIVE/FROTH FLOTATION[129, 130]

Recovery (Physical)



Process Description

Spent Insulated Copper Wire/Cable[131]

↓

Separation → Copper

↓ Wire Insulator

Shredding

↓

Screening

↓ Plastic Bits

Flotation[132] (in aluminium sulphate electrolyte) ← pH Adjustment (using HCl and NaOH); Flotation Reagents (e.g., Calcium Lignosulphonate and Polyvinyl Alcohol)

↓

Rinsing

↓

Drying[133] → Separated Plastic

WAC

- Not specified

Current Application

- Laboratory-scale study

Advantages

- Enables separation of same plastic types, which makes recycling of plastic wastes easier due to homogeneity.

Limitations

- pH of solution plays an important role in flotation separation.

Recommendations/ Further Research Required

- Further studies should be carried out on different waste cable insulator types to find the suitable pH for the selective flotation process.

T R L 4

Technology validated in lab

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129 T Takoungsakdakun and S Pongstabodee, *Separation of mixed post-consumer PET-POM-PVC plastic waste using selective flotation*, 2007.

130 N T T Truc and B K Lee, *Sustainable and Selective Separation of PVC and ABS from a WEEE Plastic Mixture Using Microwave and/or Mild-Heat Treatment with Froth Flotation*, 2016.

131 Copper wire will be separated to obtain the plastic wire insulator, which will undergo shredding and screening.

132 During flotation, the froth will pass through a gutter by overflow, and each type of plastic waste will be collected via a sieve.

133 Mixed plastic bits will be separated based on the hydrophilic states of the surfaces through the variation in pH and air flow rate.

HOT WATER SEPARATION[134, 135, 136]

Recovery (Physical)

Process Description

Spent Insulated Copper Wire/Cable

↓

Cutting (into shorter lengths)

↓

Blending ← Hot Water

↓

Filtration[137] → Copper

↓ Unliberated Wire

Heavy Liquid Separation[138] (Using carbon tetrachloride and tetrabromoethane) → Insulator

↓

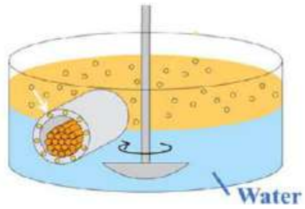
Copper

WAC

- Copper wires to be cut into shorter lengths

Current Application

- Laboratory-scale study



Advantages

- Can achieve separation rate of nearly 100%.
- Cables do not have to be grinded into smaller pieces.
- The required cleanness of products and energy savings by less grinding stages can be achieved.
- Suitable for recycling all types of cable wastes, including oil-containing cables.
- Recovered insulating material after the process is absolutely metal-free.

Limitations

- Cutting length, water temperature and blending speed affects the separation rate, so wires of different diameter require different optimum conditions.

Recommendations/ Further Research Required

- There is still a need for final design engineering for the pilot plant, defining the processes, unit operations and allows the economic evaluation.

TRL 4

Technology validated in lab

---

[134] See note 123.

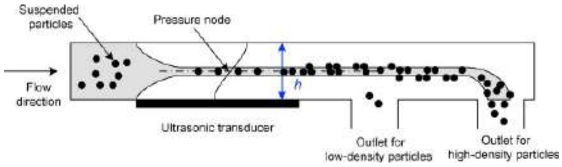
[135] J Liu *et al.*, *Separation mechanism of polyvinyl chloride and copper components from swollen electric cables by mechanical agitation*, 2019.

[136] S W Sheih and M S Tsai, *Hot water separation process for copper and insulating material recovery from electric cable waste*, 2000.

[137] A filter will be used to remove the bulk of the water remaining, and the cables will be separated into copper, wire insulator and unliberated wire (copper still with insulator), respectively.

[138] Wire insulator material will be recovered using carbon tetrachloride, and copper from unliberated wire will be recovered using tetrabromoethane.

ULTRASONIC SEPARATION[139, 140, 141]



Recovery (Physical)

Process Description

Spent Insulated Copper Wire/Cable

↓

Cutting (into shorter lengths)

↓

Water →

Ultrasonic Separation[142]

↓ Copper, Wire Insulator, Unliberated Wire

Drying

↓

Sieving → Copper

↓ Copper, Wire Insulator, Unliberated Wire

Manual Separation → Copper

→ Insulator

WAC

- Preferably copper content of >50% to improve separation rate

Current Application

- Laboratory-scale study

Advantages

- Green recycling technology that does not change the physical and chemical properties of copper and plastic.
- Great environmental benefits (such as high recovery rate, low energy consumption, etc.).

Limitations

- Different types of copper wire (different diameter and copper content) affect the separation rate.
- Cutting length, water temperature and solid-liquid ration affects the separation rate.
- Processing scale is small and difficult to achieve industrialization.

Recommendations/ Further Research Required

- Further research on the influence of relative content of coper and material of plastic on separation rate.
- Further detailed study is recommended to be conducted on the liquid-solid ratio and separation rate.

TRL 4

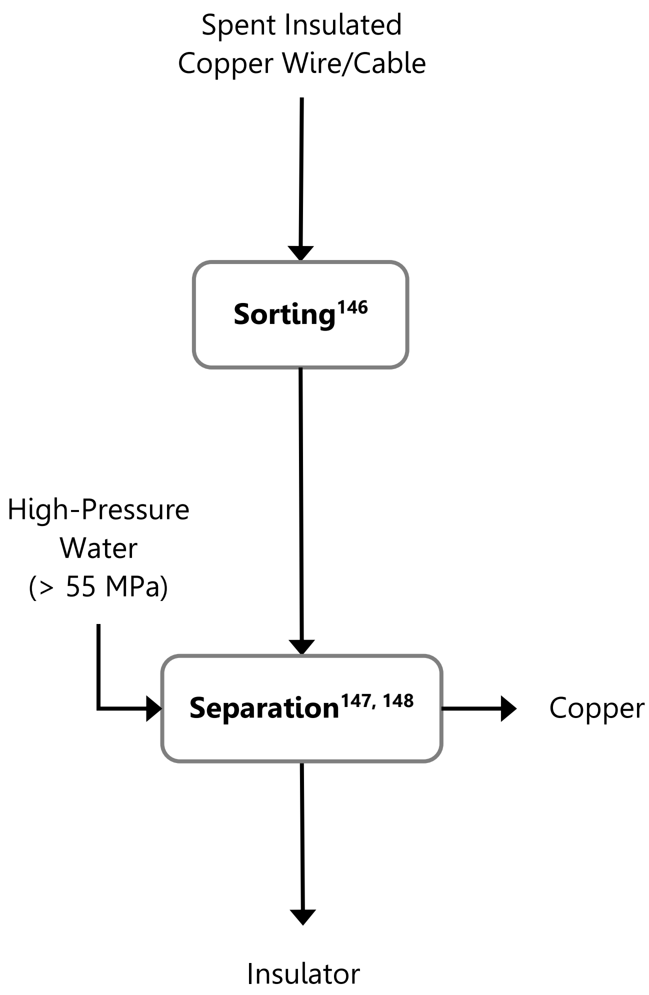
Technology validated in lab

[139] See note 123.
[140] L Li *et al.*, *Overview of the recycling technology for copper-containing cables*, 2017.
[141] Y Li *et al.*, *Recycling electrically-conductive metal and insulating material from cable waste by ultrasonic*, 2011.
[142] Separation of the wire insulator and copper is induced by ultrasonic waves that goes through the water using cavitation phenomenon, causing the spent insulated wire and cables to sway and vibrate.

HIGH-PRESSURE WATER JET TECHNOLOGY[143, 144, 145]

Recovery (Physical)

Process Description



Advantages

- Does not change the physical and chemical properties of treated materials.
- Uses cold cutting and does not produce thermal deformation, thus not affecting the quality of the core.
- Simple to operate.

Limitations

- Low degree of automation and requires workers to monitor operation process in real time.
- Waste of a substantial portion of energy.
- Requires appropriate pressure to cut off the insulator layer from the copper core, yet not destroying the core.

Recommendations/ Further Research Required

- Improvement of the working platform and control system is required.
- Requires more study, particularly on the large-scale automated processing equipment, to achieve industrialization.

WAC

- Sorted based on type of cable

Current Application

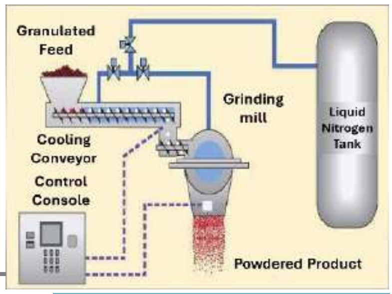
- Laboratory-scale study

T R L 4

Technology validated in lab

[143] See note 123.
[144] K He *et al., Patent No. CN103198906A*, 2013.
[145] See note 140.
[146] Spent insulated cables and wires will be sorted by reeling and wounding according to specific types.
[147] The free end of the spent insulated cables and wires reel will be positioned underneath the nozzle of the high-pressure water jet.
[148] Spent insulated cables and wires will move uniformly relative to the high-pressure water jet, causing a pressure transient on the surface of the insulator, which results in tearing in a short time.

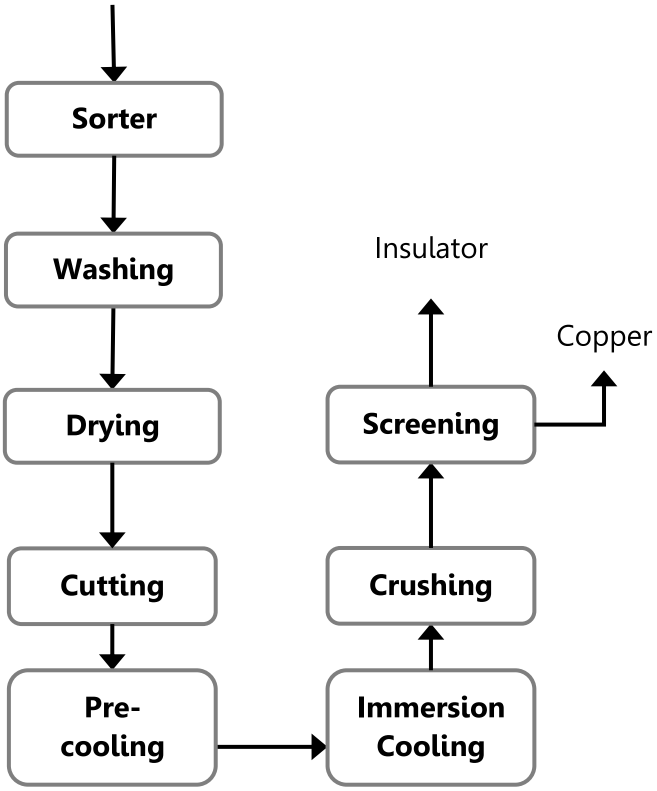
CRYOGENIC GRINDING TECHNOLOGY (FREEZING PROCESS)[149, 150, 151]



Recovery (Physical)

Process Description

Spent Insulated Copper Wire/Cable[152]



WAC

- Cables that cannot be easily crushed at room temperature, such as cables containing polypropylene (PP), low-density polyethylene (LDPE), high-density polyethylene (HDPE), and ultra-high molecular weight PE

Current Application

- Technology applied on waste plastic scraps but failed to commercialize due to costs

Advantages

- Green recycling technology that does not change the physical and chemical properties of copper and plastic.
- Great environmental benefits like low dust pollution, low noise pollution, low crushing force and heat-sensitive materials will not oxidize and deteriorate.

Limitations

- High operation costs caused by using liquid nitrogen.
- Processing scale is small and difficult to achieve industrialization.
- Not suitable for all waste cable types.

Recommendations/ Further Research Required

- Imperative to develop efficient refrigeration technology and optimize process flow of cryogenic grinding to decrease the cost.

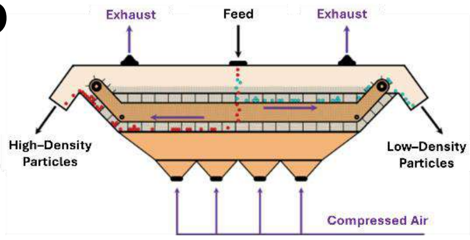
TRL 8

System complete and qualified

[149] See note 123.
[150] See note 140.
[151] K Sacthivel, S Sahana and K G A Goonasekere, *Methods to Increase the Grinding Efficiency of Spices – A Review*, 2020.
[152] Spent insulated cables and wires will be treated with appropriate refrigerant, usually liquid nitrogen – an inert substance, to make the plastic material more brittle, making it easy to crush, whereas the copper core retains its strength.

GRAVITY/DENSITY-BASED SEPARATION[153, 154, 155]

Recovery (Physical)



Process Description

Spent Insulated Copper Wire/Cable

↓

Grinding

↓

Gravity Separation[156. 157] → Copper

↓

Insulator

WAC

- Particle size of 5 – 150 mm

Current Application

- Practiced by industry players

Advantages

- Density-based separation processes have found widespread application in non-metal/metal separation.

Limitations

- Large energy consumption and low separation efficiency.
- Requires close size control of feeds to reduce the size effect and make the relative motion of the particle specific gravity dependent.

Recommendations/ Further Research Required

- Further research is required prior to implementation.

TRL 9

Actual system proven in operational environment

153 See note 123.
154 Copper-recycle, *Air Gravity Separator*, undated.
155 J Cui and E Forssberg, *Mechanical recycling of waste electric and electronic equipment: a review*, 2003.
156 Gravity separator will use a combination of air, vibration and separation to separate the wire insulator and copper core.
157 The motion of a particle in a fluid is dependent on the particle's density, size and shape, large particles being affected more than smaller ones.

ELECTROSTATIC SEPARATION[158, 159, 160]

Recovery (Physical)

Process Description

Spent Insulated Copper Wire/Cable

↓

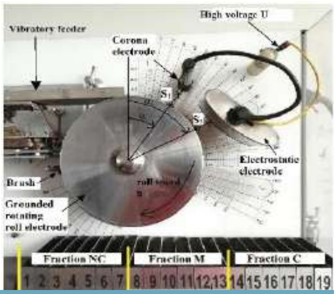
Grinding[161]

↓

Electrostatic Separation[162] → Copper

↓

Insulator



Advantages

- Low power usage.
- Low maintenance and exploitation cost.
- Able to obtain metal-free product.
- High separation efficiency (copper and plastics up to 99%).

Limitations

- Specific resistance of certain types of flexible PVC and rubber used to make cables have low resistivity, and discharge time constant of the non-conductor may fall below 1s, which makes the process difficult.

Recommendations/ Further Research Required

- Requires studies to estimate the optimal conditions of the process variables on the separation efficiency.

WAC

- Particle size of 0.1 – 5mm

Current Application

- Practiced by industry players

T R L 9

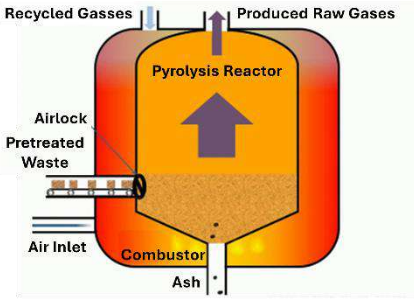
Actual system proven in operational environment

---

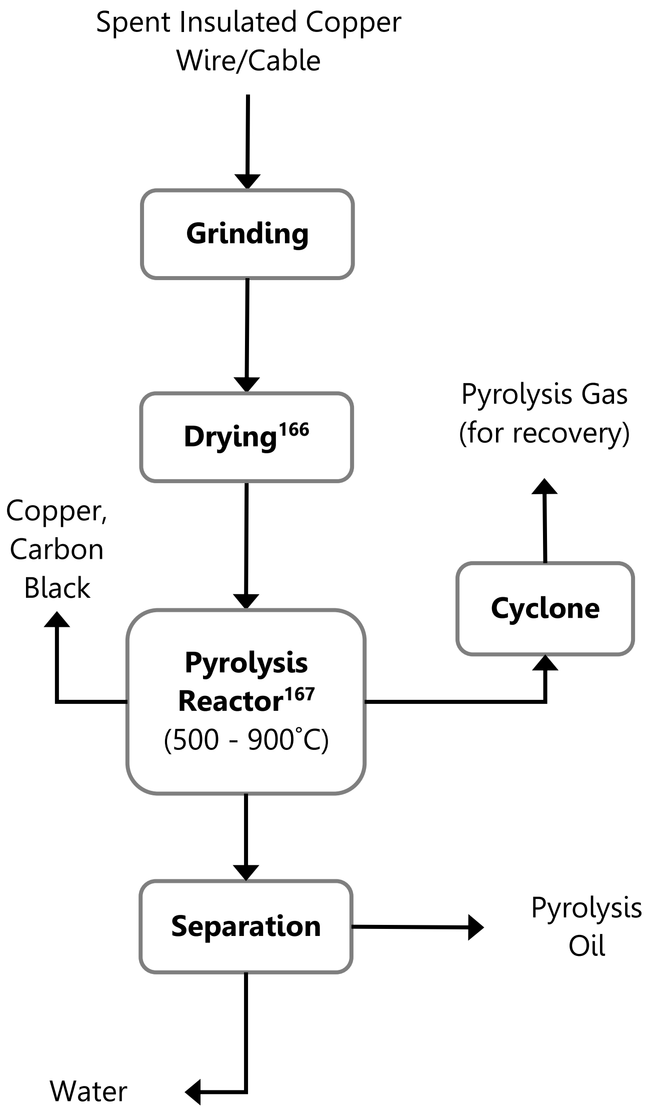
158 See note 123.
159 A Catinean *et al., Improving the recovery of copper from electric cable waste derived from automotive industry by corona-electrostatic separation*, 2018.
160 See note 155.
161 Ground spent insulated copper wire and cable will be fed to the electrostatic separator where the materials are separated into conductive and non-conductive fractions using corona charging.
162 Copper is negatively charged while moving towards the edge of electrode by vibrating energy whereas the net charge on the plastics remains unchanged. Negatively-induced copper particles will be repelled from the (-) electrode of same polarity and are deflected to (+) electrode under influence of the electric field between the electrodes.

PYROLYSIS[163, 164, 165]

Recovery (Thermal)



Process Description



Advantages

- Problems like oxidation of copper and formation of toxic gas will not occur.

Limitations

- The complexity and diversity of cable fillers may cause the optimization condition for pyrolysis of waste cables difficult.

Recommendations/ Further Research Required

- More attention should be paid to better understand the pyrolysis mechanisms and optimization of kinetic parameters.
- Limitations in complexity and diversity of cable fillers in the real situation should be considered.

WAC

- < 0.2 mm size dried waste cable particles

Current Application

- Laboratory-scale study

TRL 4

Technology validated in lab

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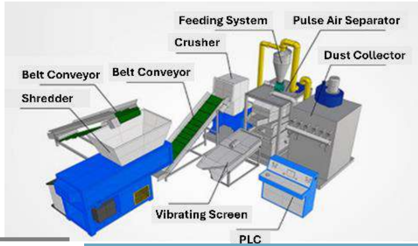
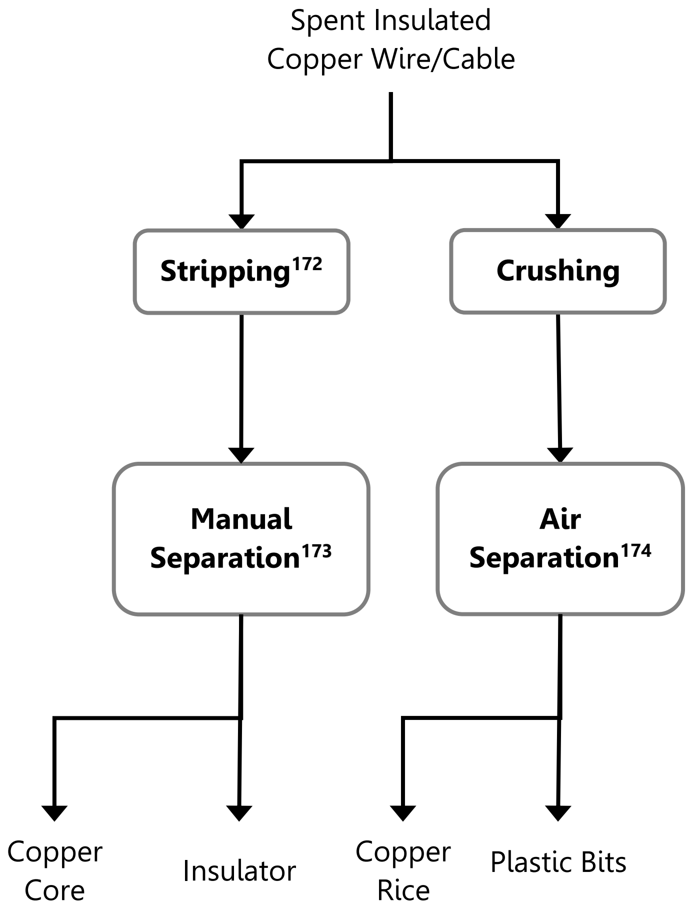
163 Biofuels Edu, *Process of Pyrolysis*, 2013.
164 See note 123.
165 Z Wang, S hostikka and J Wang, *Pyrolysis behavior and kinetic analysis of waste polypropylene-based complex for cable filler*, 2022.
166 Particles will then be dried at 80˚C for about 24 h to completely remove free water.
167 Pyrolytic gas (fuel gas), fuel oil, and carbon black are obtained from pyrolysis of waste-cables sheaths, and copper remains in the metallic state.

MECHANICAL RECYCLING[168, 169, 170, 171]

Recovery (Physical)



Process Description



Advantages

- Simple, low-cost and has strong adaptability.

Limitations

Stripping

- Application scale is deeply confined; it can only be applied to stripping a particular wire/cable of certain diameter.

Crushing

- Requires initial manual cutting and leads to severe human resource waste and low efficiency.
- Friction between equipment and waste cables produces high temperature and heat, resulting in wearing and operational failure of the copper rice. machine.

Recommendations/ Further Research Required

- Development of high efficiency and low consumption waste cables cutting, and sorting technology and equipment to improve this industry's efficiency and working conditions.

WAC

- Not specified

Current Application

- Practiced by industry players

T R L 9

Actual system proven in operational environment

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[168] See note 123.
[169] See note 155.
[170] See note 159.
[171] K Lee, *Characteristics of Copper Wire Granulator Equipment*, 2022.
[172] The stripping machine will strip the insulation by a blade or a knife, while an operator will feed the cable into a feed port, and an electric motor will pull the wire through.
[173] The operator will then peel the cable manually, or the insulation falls off, depending on the thickness of the cable and/or conditions.
[174] Waste cables will be crushed into particles of particular size after passing the crushers and then separated with sorting equipment into plastic bits and copper rice.

4.2.5 SW 202 – Spent Catalysts

Catalysts are substances that accelerate chemical reactions without being consumed in the process.[175] There are various types of catalysts, but they are generally categorized as homogeneous and heterogeneous.

Homogeneous catalysts exhibit advantages in terms of activity and stability due to their good solubility in reaction media, but they are difficult to separate and recover from the reaction mixture.[176] Thus, the usage of homogeneous catalysts is generally limited to non-drug and pharmaceutical industries as there may be an issue of metal contamination. Meanwhile, even though heterogeneous catalysts are easily recovered, they are generally less efficient as compared to the homogeneous counterpart.[177]

Once the catalysts have completed their lifespan and can no longer perform their original duty, they are considered "spent".[178] The chemical composition of spent catalysts highly varies across different refineries and industries, but typically contain metals, metal oxides, metal sulphides etc.[179] Examples on the chemical composition of spent catalysts from two (2) refineries in Oman can be referred in **Table 4-10**.

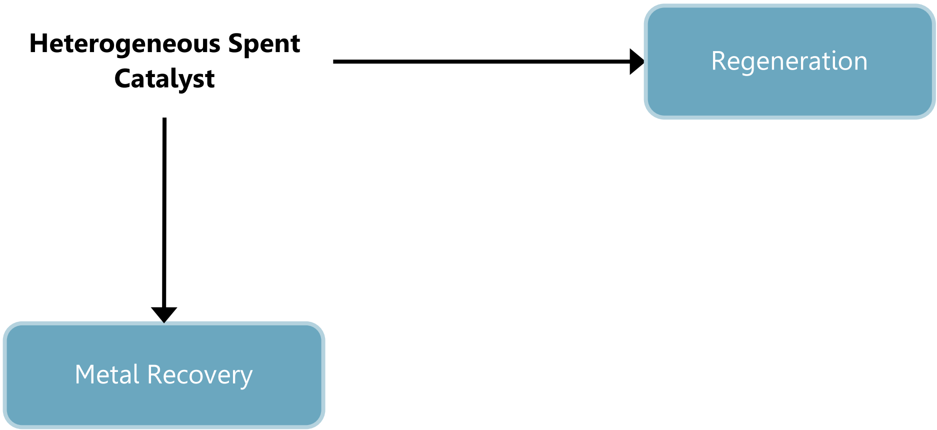
Table 4-10: Examples on Chemical Composition of Spent Catalyst[180]

Chemical Components	Composition (%)	
	Refinery 1	Refinery 2
SiO_2	1.71	39.21
Al_2O_3	66.66	37.68
Fe_2O_3	0.07	0.66
CaO	0.08	0.05
MgO	0.02	0.26
Na_2O	8.29	0.43
K_2O	0.26	0.06
Loss-on-ignition (LOI)	26.13	2.43

The presence of heavy metals, coke, and other toxic elements makes these spent catalysts hazardous wastes.[181] Rather than disposal, spent catalysts can be regenerated and activated effectively or undergo metal recovery to minimize discarded materials in the refining industry[182, 183] (**Figure 4-4**).

[175] L Hamers, *Explainer: What is a catalyst*, 2022.
[176] M Miceli *et al.*, *Recovery/Reuse of Heterogeneous Supported Spent Catalysts*, 2011.
[177] ibid.
[178] See note 176.
[179] S Sulaiman, *Waste Management in Petroleum Refinery Spent Catalyst*, 2011.
[180] K Al-Jabri *et al.*, *Potential use of FCC spent catalyst as partial replacement of cement or sand in cement mortars*, 2013.
[181] See note 176.
[182] See note 176.
[183] J C Chen and J J Huang, *Regeneration of spent catalysts by H_2O_2 chemical treatment*, 2013.

Figure 4-4: Recovery Pathways of Spent Catalyst



4.2.5.1 Reuse Applications

There are no reuse applications for spent catalysts under the reuse category as defined in **Chapter 3.3, Table 3-1**.

4.2.5.2 Recovery Technologies

Recovery technologies for spent catalysts generally comprises of physical and chemical methods. A variety of processing approaches for rejuvenating/regenerating the spent catalysts or recovering metals from spent catalysts are explored in this Chapter, and a summary of recovery technologies can be referred in **Table 4-11**.

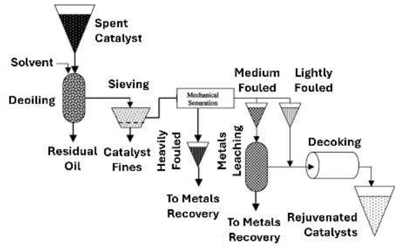
Table 4-11: Summary of Recovery Technologies for SW 202 (Spent Catalysts)

Recovery Technologies	Method	Technology Readiness Level (TRL)	Reference Page
Rejuvenation process	Physical & Chemical	4 *Technology validated in lab*	4-50
Regeneration via H_2O_2 chemical treatment	Chemical	7 *System prototype demonstration in operational environment*	4-51
Centrifugation	Physical	9 *Actual system proven in operational environment*	4-52
Filtration	Physical	9 *Actual system proven in operational environment*	4-53
Magnetic separation	Physical	9 *Actual system proven in operational environment*	4-54
Combination of alkaline leaching and ion exchange	Chemical & Physical	9 *Actual system proven in operational environment*	4-55

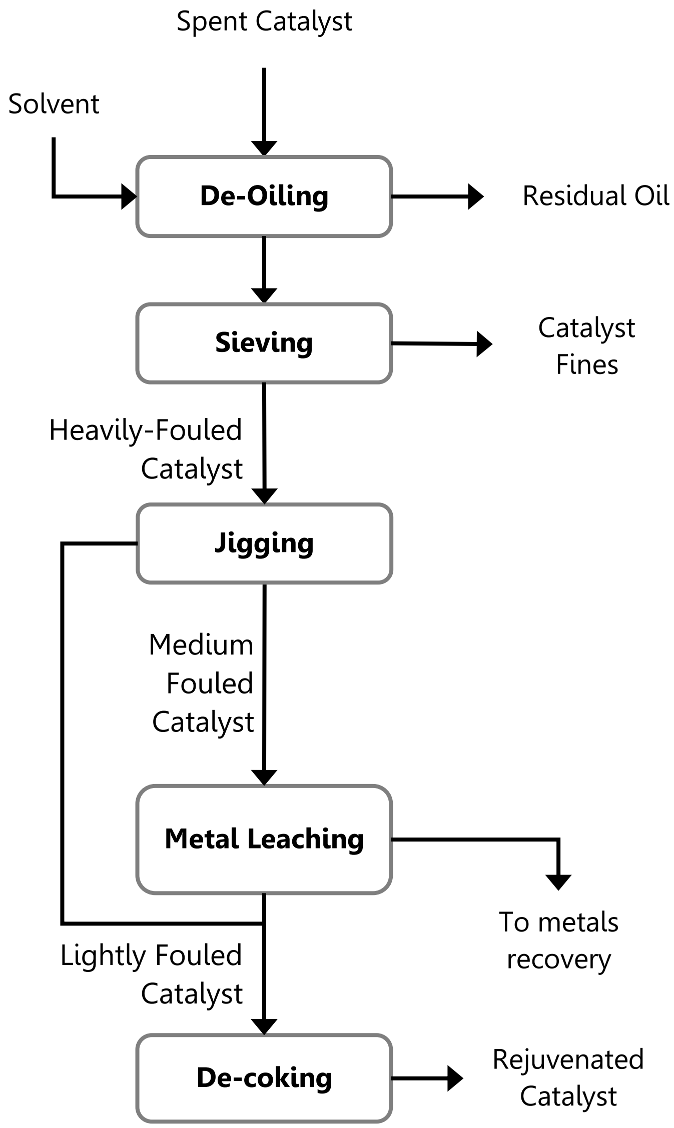
Recovery Technologies	Method	Technology Readiness Level (TRL)	Reference Page
Ion exchange	Physical	9 *Actual system proven in operational environment*	4-56
Tetronics' DC plasma arc technology	Thermal	9 *Actual system proven in operational environment*	4-57
Biometallurgy	Biological	9 *Actual system proven in operational environment*	4-58

REJUVENATION PROCESS[184, 185]

Recovery (Physical & Chemical)



Process Description[186]



WAC

- Spent hydroprocessing catalysts from refineries

Current Application

- Laboratory-scale study

Advantages

- Up to 70% of the spent catalyst can be reclaimed in the process with activity as high as 95% of fresh catalyst.
- Economic assessment of the process revealed that rejuvenation and reuse of the catalyst is feasible with an internal rate of return (IRR) of 20%.

Limitations

- Will generate further waste products and air emissions.

Recommendations/ Further Research Required

- Further improvement can be realized when a state-of-the-art control system is incorporated into the detailed engineering design for emissions control and waste minimization.

TRL 4

Technology validated in lab

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[184] M Marafi and A Stanislaus, *Spent catalyst waste management: A review*, 2008.
[185] M Marafi, A Stanislaus and E Kam, *A preliminary process design and economic assessment of a catalyst*, 2008.
[186] The process consists of several operations such as de-oiling, sieving, separation of heavily fouled catalysts from the partly fouled portions by jigging, metal leaching and decoking to produce rejuvenated catalysts from partly fouled spent catalyst portions and sending the heavily fouled portion for metal recovery.

REGENERATION VIA H_2O_2 CHEMICAL TREATMENT[187]

Recovery (Chemical)

Process Description

Spent Catalyst[188]

↓

Chemical Regeneration[189]
(rotated and shaken for 1.5 hours in H_2O_2)

↓

Drying[190]
(at 105˚C for 2 hours)

↓

Regenerated Catalysts

WAC

- Not specified

Current Application

- Laboratory-scale study for H_2O_2, but chemical treatment is one of the popular regeneration methods

Advantages

- Effective to recover the activity of catalysts.
- Accumulated carbons or residues can be washed out and removed by H_2O_2 solution.

Limitations

- Characteristics of regenerated catalysts will be different with those of spent catalysts.

Recommendations/ Further Research Required

- Concentrations of H_2O_2 should be carefully controlled to avoid over-oxidation and erosion.

T R L 7

System prototype demonstration in operational environment

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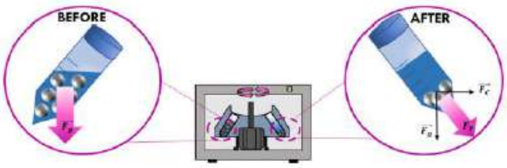
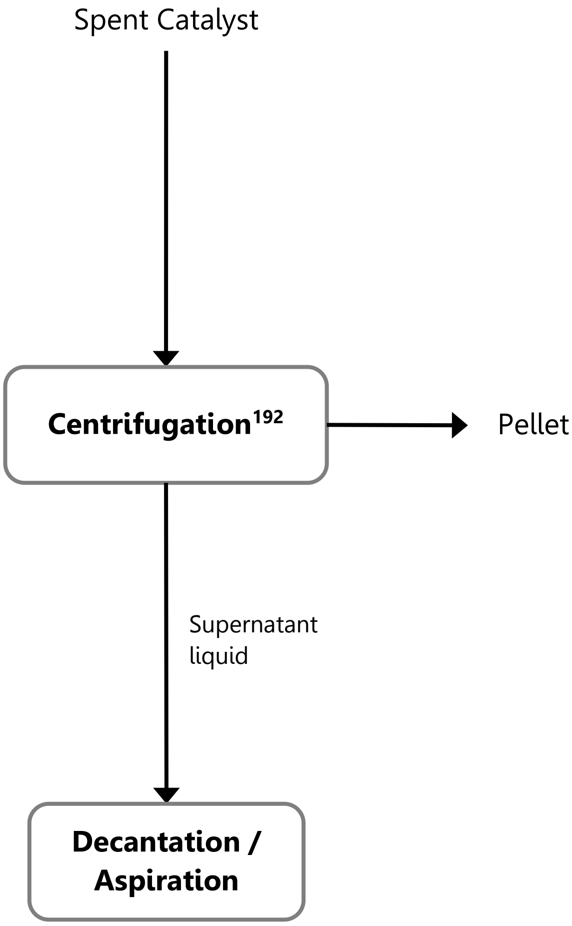
[187] J C Chen and J J Huang, *Regeneration of spent catalysts by H_2O_2 chemical treatment* , 2013.
[188] Spent catalysts will be immersed in H_2O_2 (chemical reagent) contained in vessels. Silica catalysts cannot be regenerated.
[189] The vessels are then rotated and shaken for 1.5 hours.
[190] After chemical regeneration, the catalysts will be dried at 105˚C for 2 hours.

CENTRIFUGATION[191]

Recovery (Physical)



Process Description



Advantages

- Rapid and efficient method.

Limitations

- Uneconomic process that cannot be carried out on an industrial scale.
- Not usually able to collect the nano-sized catalysts without weight loss.

Recommendations/ Further Research Required

- Need to consider the compatibility of separation technique with catalyst properties, which depends on nature of the catalyst material, time requirements, and energy consumption.

WAC

- Spent heterogenous catalysts
- Low viscosity liquid media

Current Application

- Practiced by current local industry

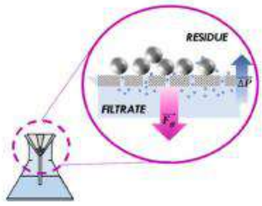
TRL 9

Actual system proven in operational environment

[191] See note 176.
[192] Centrifugation is a technique frequently used to separate mixtures of two or more phases on the basis of their different density. Separation of heterogeneous mixtures through centrifugal force helps accelerate the process. The centrifugal force provided by a centrifuge in combination with gravitational force cause particles to move radially away from the axis of rotation. More dense particles of the mixture tend to move at the bottom of the tube, while less dense particles of the mixture migrate towards the axis of the centrifuge.

FILTRATION[193]

Recovery (Physical)



Process Description

Spent Catalyst

↓

Filtration[194] → Filtrate

↓

Residue

Advantages

- Low energy consumption.
- Easy recovery.

Limitations

- Separation of phases by filtration is never complete.
- Recovery of solid catalysts after separation from reaction mixture by filtration methods very often requires further treatments such as washing, deliquoring (elimination of liquid from the filter by mechanical forces), and thermal drying.
- Tedious and time consuming.

Recommendations/ Further Research Required

- Need to consider the compatibility of separation technique with catalyst properties, which depends on nature of the catalyst material, time requirements, and energy consumption.

WAC

- Spent heterogenous catalysts
- Low viscosity liquid media

Current Application

- Practiced by overseas industries, e.g. Italy, US
- Practiced by local industries

T R L 9

Actual system proven in operational environment

[193] See note 176.
[194] Filtration exploits the different size of the components of the mixture to separate an undissolved solid from a liquid or a gas. The technique involves the use of a porous structure (filter/membrane) called septum that allows the fluid phase of mixture to pass through but keeps larger solid particles back. As the liquid/solid material passes through the filter, the solid material is collected and removed. There are a few filtration processes, namely gravity filtration, centrifugal filtration, pressure filtration and vacuum filtration.

MAGNETIC SEPARATION[195]

Recovery (Physical)

Process Description

Spent Catalyst

↓

Magnetic Separation[196]

↓

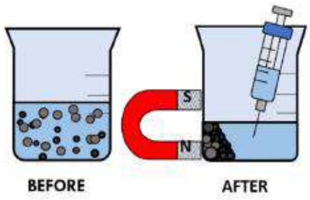
Catalyst

WAC

- Magnetic solid catalysts

Current Application

- Practiced by overseas industries



Advantages

- Fast, simple, convenient and efficient method.
- Makes the work-up procedure economically and technically feasible with a minimal loss of solid catalyst.
- Reduces secondary waste generation and energy consumption.

Limitations

- MNPs commonly tend to agglomerate into a large cluster due to their small interparticle distances, high surface energy, and the existence of van der Waals forces.

Recommendations/ Further Research Required

- Opportunity to expand the use of expensive catalysts based on noble metals and rare-earth elements.

TRL 9

Actual system proven in operational environment

[195] See note 176.

[196] Separation of magnetic solid catalysts can be conducted using an external magnet, i.e., Magnetic Nanoparticles (MNP). The process of synthesis of functionalized magnetic nanoparticles usually consists of three steps: the formation of the magnetic core, the coating of the nanoparticles with an outer shell and the modification of the resultant core-shell structure.

COMBINATION OF ALKALINE LEACHING AND ION EXCHANGE[197]

Recovery (Chemical & Physical)

Process Description

Spent Catalyst

↓

Grinding[198]

↓

Sieving

↓

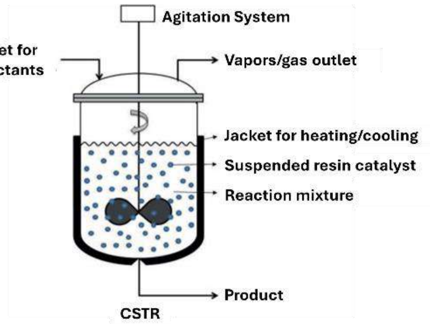
Leaching[199] (at 70˚C, 400 rpm for 30 mins.) ← Distilled Water[199] and NaOH

↓

Filtration[200] → Filtrate (containing extracted metals) → **Ion Exchange[201]**

Filtration[200] ↓ Residual Particles

Ion Exchange[201] ↓ Effluent (can be further processed)



Advantages

- Effective and easy to operate.

Limitations

- Produces large amount of residual waste liquid.

Recommendations/ Further Research Required

- Studies on the NaOH concentration, pulp density, temperature, particle size, leaching time, effluent volume and pH should be conducted to find the optimal conditions for this process.

WAC

- Spent selective catalytic reduction (SCR) catalyst grounded to particle size of -74μm

Current Application

- Practiced by overseas industries

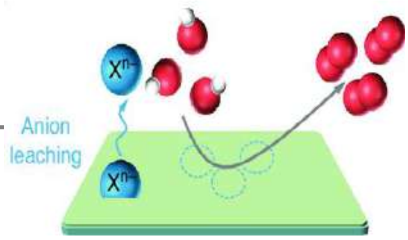
T R L 9

Actual system proven in operational environment

[197] W Wu, T Tsai and Y Shen, *Tungsten Recovery from Spent SCR Catalyst Using Alkaline Leaching and Exchange*, 2016.
[198] The spent catalyst was ground and sieved using various mesh-size sieves.
[199] The required amounts of distilled water and NaOH were transferred to the reactor and placed in a water bath. Once the test temperature was reached, a calculated amount of catalyst sample was added to the reactor.
[200] The final solution was filtered to eliminate residual particles.
[201] The filtrate will then undergo separation with anion exchange resin, which can be carried out in a glass column.

ION EXCHANGE[202, 203]

Recovery (Physical)



Process Description

Spent Catalyst

↓

Ion Exchange
via
i) Batch adsorption (stirring at 150 rpm, at room temp.)[204]
ii) Column[205]

↓

Suspension

Advantages

- Effective and easy to operate.

Limitations

- Produces large amount of residual waste liquid.

Recommendations/ Further Research Required

- Studies on the NaOH concentration, pulp density, temperature, particle size, leaching time, effluent volume and pH should be conducted to find the optimal conditions for this process.

WAC

- Spent catalyst from petroleum-refining industries

Current Application

- Practiced by overseas industries

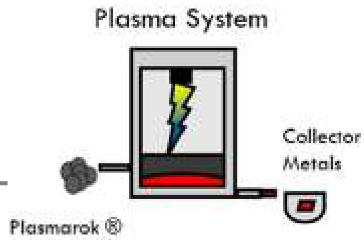
TRL 9

Actual system proven in operational environment

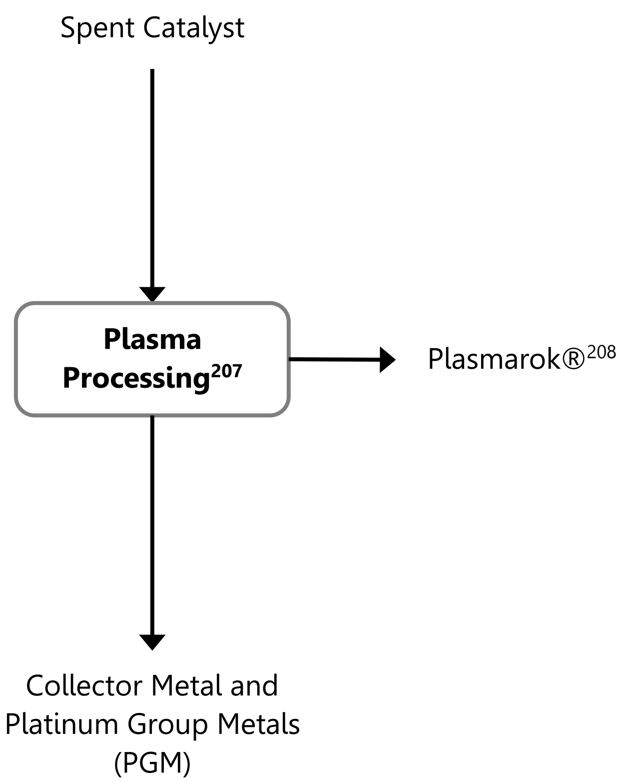
[202] D Guan *et al.*, *Utilizing ion leaching effects for achieving high oxygen-evolving performance on hybrid nanocomposite with self-optimized behaviours*, 2020.
[203] J Hu *et al.*, *Removal of vanadium from molybdate solution by ion exchange*, 2009.
[204]Batch adsorption - Spent catalysts and wet resin will be agitated at 150 rpm, at room temperature (25 ± 0.5°C). After adsorption, the suspension can be filtered.
[205] Column - Spent catalysts will be treated with NaOH and HCl prior to wet-packing into the glass column. The operation can be performed by downstream flow at a constant flow rate of 30 ml/h.

TETRONICS' DC PLASMA ARC TECHNOLOGY[206]

Recovery (Thermal)



Process Description



Advantages

- No toxic gases such as dioxins and furans (destroyed through plasma melting).
- No waste liquid.
- Recovery of non-valuable solid residue known as Plasmarok® that can be reused in a range of building applications.
- No ash produced.

Limitations

- Mainly used to recover PGM from specific catalyst groups.

Recommendations/ Further Research Required

- Further research is required before implementation.

WAC

- Spent autocatalyst and industrial catalyst

Current Application

- Practiced by overseas industries in automotive and industrial catalysts

T R L 9

Actual system proven in operational environment

206 See note 176.
207 Plasma processing uses a plasma arc created by either a single or multiple electrodes/torch as a heat source to smelt metals. The high energy content of the plasma converts the organic components into small molecules, whereas the inorganic and metal components are melted to form slag and metal slag.
208 Non-valuable solid residue recovered from the Tetronics' DC Plasma Arc process, called Plasmarok®, having been subjected to extreme heat, presents itself as an inert, non- hazardous molten vitreous material, that, if cooled slowly, can be harder and more stable than granite and, hence, can be reused in a range of building applications.

BIOMETALLURGY[209, 210]

Recovery (Biological)

Process Description

Spent Catalyst

↓

Pretreatment
(Heating in furnace at 600°C for 4 hours)

↓ Decoked Spent Catalyst

Grinding

↓

Sieving

↓

Bioleaching[211]
(containing Sucrose Medium)

← Acclimated Microorganisms such as Bacteria or Fungi, e.g., *Aspergillus Niger*

↓

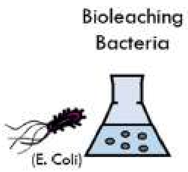
Residue containing heavy metal ions (e.g., Ni, Mo, Fe, Al and W)

WAC

- Pretreated spent catalyst

Current Application

- Practiced by overseas industries



Advantages

- Environmentally friendly.
- Mild operating condition requirements.
- Low cost.
- Relatively simple.
- Low energy requirement.
- Reduced skilled labour requirements.

Limitations

- Longer time required for extraction compared to conventional chemical leaching.

Recommendations/ Further Research Required

- Optimization of bioleaching method using specific microorganisms, such as *Aspergillus Niger*, to obtain higher efficiencies and rates of recovery, while minimizing process cost.

T R L 9

Actual system proven in operational environment

---

[209] See note 176.
[210] Amiri *et al., Recovery of metals from spent refinery hydrocracking catalyst using adapted Aspergillus niger*, 2013.
[211] Bioleaching can be done in three different methods:
i) The first method is one-step bioleaching, in which the fungus was incubated together with the medium and spent catalyst.
ii) The second method was two-step bioleaching, in which the fungus was first cultured in sucrose medium without the spent catalyst for 2 days and then, following a decrease in pH (beginning of organic acid production), the sterilized catalyst was added.
iii) The third method was spent medium leaching, which was performed by culturing the fungus in sucrose medium for 10 days.

4.2.6 SW 204 – Sludge Containing Heavy Metals from Paper Mill

Heavy metal sludges from paper mill industries may be generated from three (3) main sources: screening process, papermaking process (primary sludge) and wastewater treatment process (secondary or biological sludge).

The sludge from screening process is produced during filtration steps with screens of very small slots, which helps to remove pulp possibly containing components that could negatively impact the production process and the end product quality.[212] This sludge from screening process has a relatively low moisture content and a significant amount of cellulose fibre.[213]

Primary sludge generated from the papermaking process comes from the clarification of process water via kidney treatments such as dissolved air flotation.[214] The composition of this sludge primarily comprises of fines and fillers, which varies depending on the type of recovered paper being processed.[215] Usually, these types of sludge are reused back into the board industry production processes; however, for high-grade products, primary sludge may be incinerated, disposed, or blended with secondary sludge.[216, 217]

Secondary or biological sludge is produced in the clarifier of the wastewater treatment units within paper mills and are usually recycled back into the board industry's production process or sent to the thickening process prior to dewatering.[218] The dewatered secondary sludge will usually be incinerated or disposed in landfills. Compared to the primary sludge, the volume of secondary sludge is much lesser due to the removal of most heavy, fibrous, or inorganic solids in the primary clarifier.[219] Nonetheless, secondary sludges can be a challenge to manage due to their high content of microbial protein; hence, it often has to be blended with primary sludges to facilitate effective dewatering.[220]

Typical composition of sludge from the screening process includes impurities, such as plastics, fibres, glass and stones, some metals and organic solids. Meanwhile, primary and secondary sludge compositions obtained from a local player, GS Paperboard and Packaging Sdn. Bhd. (GSPP), and from the European Commission's Best Available Techniques (BAT) Reference Document for the Production of Pulp, Paper and Board are summarized in **Table 4-12**.

[212] P Bajpai, *Management of Pulp and Paper Mill Waste*, 2015, 10.
[213] ibid.
[214] See note 212.
[215] See note 212.
[216] See note 212.
[217] GS Paperboard and Packaging Sdn. Bhd., 2023.
[218] See note 212.
[219] See note 212.
[220] See note 212.

Table 4-12: Typical Composition of Primary and Secondary Sludge[221, 222, 223]

Parameter	Primary Sludge		Secondary Sludge	
	GSPP	EU	GSPP	EU
Dry solid (DS) content	-	47.9 %	-	31.7 %
Organic solids	-	33.2 %DS	-	48.3 %DS
TOC	-	19 %DS		23 %DS
Antimony	-	-	<25 mg/kg	-
Arsenic	ND [224] (<0.01 mg/kg)	1.6 mg/kg DS	2 mg/kg	2.3 mg/kg DS
Barium	27.9 mg/kg	-	61 mg/kg	-
Beryllium	-	-	<25 mg/kg	-
Lead	38.1 mg/kg	41 mg/kg DS	152 mg/kg	22 mg/kg DS
Cadmium	0.9 mg/kg	<0.67 mg/kg DS	<2 mg/kg	<0.67 mg/kg DS
$Chromium_{Total}$	6.5 mg/kg	24 mg/kg DS	36 mg/kg	17 mg/kg DS
Cobalt	-	-	<25 mg/kg	-
Copper	87.4 mg/kg	238 mg/kg DS	130 mg/kg	71 mg/kg DS
Nickel	3.2 mg/kg	5.7 mg/kg DS	65 mg/kg	7.5 mg/kg DS
Mercury	ND (<0.02 mg/kg)	0.08 mg/kg DS	<25 mg/kg	0.09 mg/kg DS
Molybdenum	-	-	<25 mg/kg	-
Selenium	-	-	<25 mg/kg	-
Silver	ND (<0.01 mg/kg)	-	<25 mg/kg	-
Thallium	-	-	<25 mg/kg	-
Vanadium	-	-	<25 mg/kg	-
Zinc	ND (<0.01 mg/kg)	141 mg/kg DS	465 mg/kg	135 mg/kg DS

4.2.6.1 Reuse Applications

Paper mill sludges have hydrodynamic properties which is useful to be reused as a landfill cover barrier. Apart from that, it also contains certain amount of nutrient values, which provides a possibility to explore the utilization of paper mill sludges in land applications (**Table 4-13**).

Table 4-13: Nutrient Values of Paper Mill Sludges[225, 226]

Parameters	Unit	Primary Sludge	Secondary Sludge	Combined Primary and Secondary Sludge
Phosphorus	g/kg	0.01 – 40.0	0.42 – 16.7	0.1 – 25.4
Potassium	g/kg	-	-	0.12 – 10.0
Nitrogen	% dry	<0.1 – 0.3	1.12	0.36 - 0.87

[221] ChemVi Laboratory, *Certificate of Analysis SW 204 – Paper Sludge*, 2018.
[222] Eurofins NM Laboratory, *Test Report*, 2018.
[223] M Suhr *et al.*, *Best Available Techniques (BAT) Reference Document for the Production of Pulp, Paper and Board*, 2015, 514.
[224] ND means not detected.
[225] See note 212, 86 – 87.
[226] M Likon and P Trebše, *Recent Advances in Paper Mill Sludge Management*, 2012.

Parameters	Unit	Primary Sludge	Secondary Sludge	Combined Primary and Secondary Sludge
Carbon	% dry	16.8	50.6	32.0 – 42.0
Carbon/Nitrogen ratio	-	>56	41.5	48 – 89
Ash Content	% dry	5.69 – 35.28	32.77	25.0 – 49.0

It is found that carbon/nitrogen ratios below 17-30:1 will contribute positively to the soil nitrogen balance through nitrogen mineralization, whilst ratios above 30-35:1 will act to deplete soil nitrogen (immobilization), with harmful effects on plant growth.[227]

A summary of reuse applications of paper mill sludge is presented in **Table 4-14**.

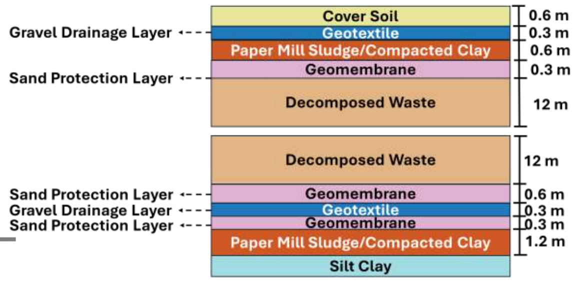
Table 4-14: Summary of Reuse Applications for SW 204 (Paper Mill Sludge)

Reuse Applications	Technology Readiness Level (TRL)	Reference Page
Animal feed production	4 *Technology validated in lab*	4-84
Reuse as landfill cover barrier	9 *Actual system proven in operational environment*	4-62
Land (Agriculture) application	9 *Actual system proven in operational environment*	4-63

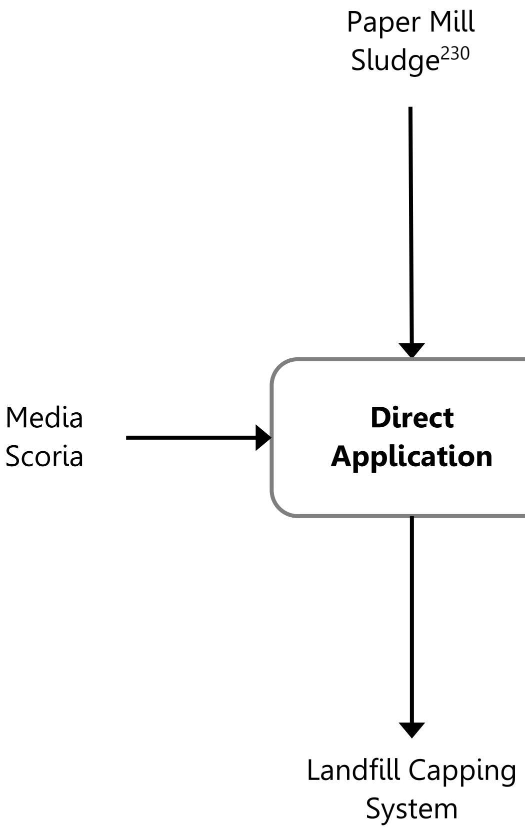
[227] See note 212, 88.

REUSE AS LANDFILL COVER BARRIER[228, 229]

Reuse



Process Description



Advantages

- Using paper mill sludge as a compacted sludge barrier layer is a low-cost, beneficial-use option.
- The performance of sludge cover barrier is equal to that of the conventional barrier systems and better than clay barriers.

Limitations

- May require improvement of strength properties of paper sludges by adding additives such as fly ash, bentonite and cement.

Recommendations/ Further Research Required

- Further research is required before implementation.

WAC

- Low hydraulic conductivity

Current Application

- Practiced by overseas industry players, e.g., Abitibi-Bowater Inc.

T R L 9

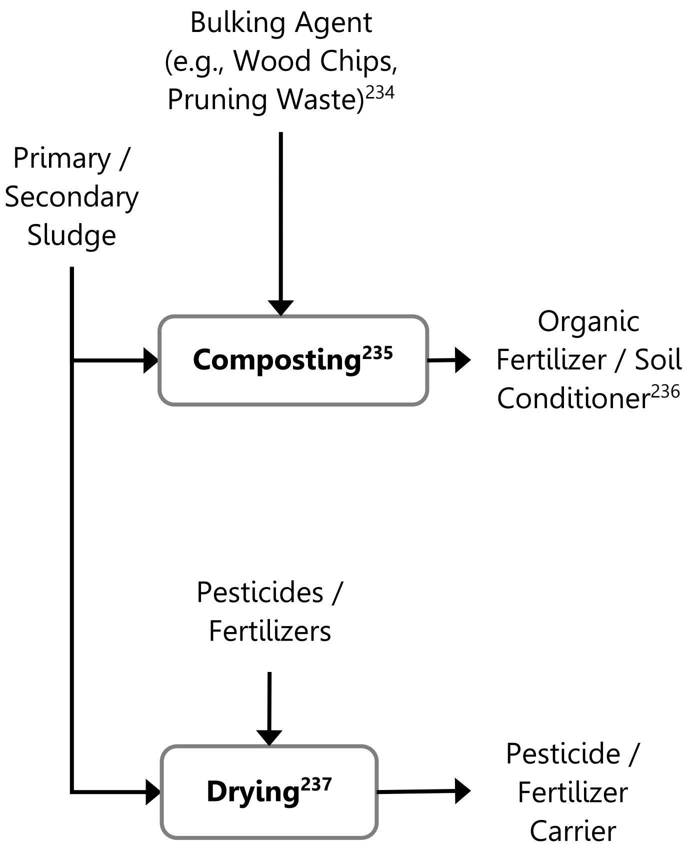
Actual system proven in operational environment

[228] See note 212, 149 – 151.
[229] M Balkaya, *Assessment of the geotechnical aspect of the use of paper mill sludge as landfill cover and bottom liner material*, 2019.
[230] Paper mill sludge, as hydrodynamic impermeable barrier, can be combined with media scoria as an oxidizing layer to build an efficient landfill capping system.

LAND (AGRICULTURE) APPLICATION[231, 232, 233]

Reuse & Recovery (Biological)

Process Description



Advantages

- Low cost disposal method.
- There can be a wide range in the nutrient values amongst sludges with the diversity of sludges produced.

Limitations

<u>Composting</u>

- Requires the application of additives in composting process.
- High space requirements, though there has been emerging in vessel technologies.

WAC

- C/N ratios < 17-30:1

Recommendations/ Further Research Required

- Further research is required before implementation.

Current Application

- Practiced by local industry players
- Practiced on a commercial scale by overseas industry players for about two decades, e.g., in USA and UK

T R L 9

Actual system proven in operational environment

[231] See note 212, 83 – 93.
[232] Department of Environmental Conservation, *Land Application*, undated.
[233] See note 226.
[234] The process microorganism breaks down the organic matter of the sludge under aerobic conditions, using bulking agents.
[235] It is a biooxidative process which involves the mineralization and partial humification of the organic matter.
[236] The stabilized final product is free of phytotoxicity and pathogens and with certain humic properties.
[237] Dried mixtures can be used as a pesticide or fertilizer carrier in agriculture which allows more controlled releasing active substances into the soil.

4.2.6.2 Recovery Technologies

Paper mill sludge has a very wide range of recovery options, ranging from reusing back into the same industry to produce lower grade paper to construction material additives, and even as an animal feed alternative. The composition of paper mill sludges makes it a highly flexible material to be utilized into different material production or as a substitute for existing materials. For example, the high inorganic fraction in paper mill sludges makes it suitable to be utilized in the production of building materials, whereas the good chemical, hydrodynamic and geotechnical properties enable the paper mill sludge to be reused as landfill capping material.

The recovery technologies for paper mill sludge includes all four (4) types of management methods, i.e., physical, biological, chemical and thermal, which are summarized in **Table 4-15**. Due to the high concentration of usable fibre (up to 40% of the sludge matrix that are > 200 mesh) which is still present in the paper mill sludge, the recovery of fibre from paper mill sludge for usage is highly studied and researched.

Table 4-15: Summary of Recovery Technologies for SW 204(Paper Mill Sludge)

Recovery Technologies	Method	Technology Readiness Level (TRL)	Reference Page
Ceramic material manufacturing	Physical, Thermal	4 *Technology validated in lab*	4-67
Plasterboard additive	Thermal	4 *Technology validated in lab*	4-68
Filler in nylon biocomposite production	Physical	4 *Technology validated in lab*	4-69
Paving and fibrous road surfacing additive	Physical	4 *Technology validated in lab*	4-70
Acid treatment to extract nanofibrils for nanocomposites	Chemical	4 *Technology validated in lab*	4-71
Oxidation for extraction of cellulose fibres to produce derivatives and/or value-added products	Chemical	4 *Technology validated in lab*	4-72
Sequential fermentation to form bacterial cellulose and enzymes	Biological	4 *Technology validated in lab*	4-73
Wood adhesive	Physico-chemical	4 *Technology validated in lab*	4-74
Simultaneous saccharification and fermentation (SSF) to produce ethanol	Biological	4 *Technology validated in lab*	4-75

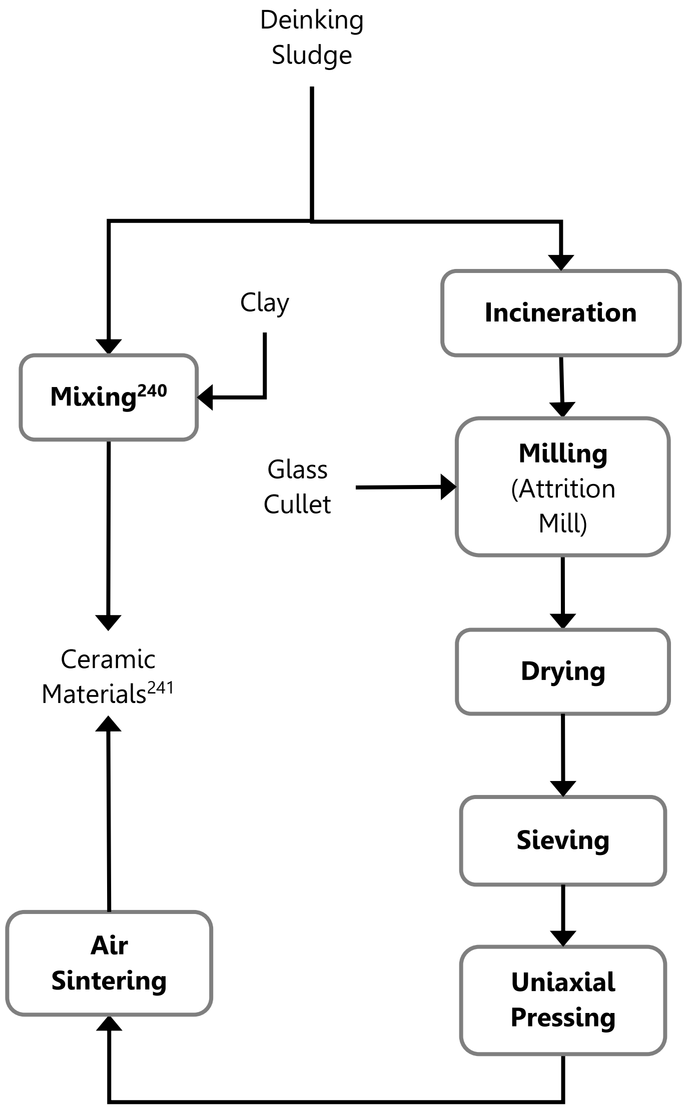
Recovery Technologies	Method	Technology Readiness Level (TRL)	Reference Page
Sorbent production via pyrolysis	Thermal	4 *Technology validated in lab*	4-76
Concrete production	Physical	6 *Technology demonstrated in relevant environment*	4-77
Fibreboard, millboard or softboard production	Physical	<u>Millboard & Softboard</u> 6 *Technology demonstrated in relevant environment* <u>Fibreboard</u> 9 *Actual system proven in operational environment*	4-81
Raw material for cement mortar products manufacturing	Physical	7 *System prototype demonstration in operational environment*	4-78
Vermicomposting	Biological	7 *System prototype demonstration in operational environment*	4-79
Anaerobic digestion	Biological	7 *System prototype demonstration in operational environment*	4-80
Raw material for insulating material production	Physical	8 *System complete and qualified*	4-82
Conversion of paper mill sludge to absorbent (CAPS) process	Physico-chemical	8 *System complete and qualified*	4-83
Animal feed production	Physical	9 *Actual system proven in operational environment*	4-84
Sorbent production via kaofin process	Physical	9 *Actual system proven in operational environment*	4-85

Recovery Technologies	Method	Technology Readiness Level (TRL)	Reference Page
Produce low-grade paper	Physical	9 *Actual system proven in operational environment*	4-86
Pyrolysis for the production of feedstock for producing biochar	Physical	9 *Actual system proven in operational environment*	4-87
Fibre recovery via screening	Physical	9 *Actual system proven in operational environment*	4-88
Processed into moulded pulp products, e.g., egg trays	Physical	9 *Actual system proven in operational environment*	4-89
Pelletization for volume reduction, odour control, recovery of fuel value and by-product applications	Physical	9 *Actual system proven in operational environment*	4-90
Wet air oxidation to recover raw materials	Thermal	9 *Actual system proven in operational environment*	4-91
Lightweight aggregates (LWA) production	Physical	9 *Actual system proven in operational environment*	4-92
Brick production	Physical	9 *Actual system proven in operational environment*	4-93
Cement and cementitious products manufacturing	Thermal	9 *Actual system proven in operational environment*	4-94

CERAMIC MATERIAL MANUFACTURING[238, 239]

Recovery (Physical, Thermal)

Process Description



WAC

- Not specified

Current Application

- Laboratory-scale study, where method has been patented.

Advantages

Mixing

- Less energy will be required for drying.
- Density of the material is decreased.

Incineration and mixing

- High quality ceramics can be produced using deinking sludge of 6-9 volume%.
- Product has low residual porosity and fine microstructure.

Limitations

Mixing

- Shape and dimensions of the material produced may not be stable as the shrinkage rate varies according to sludge used.
- Strength properties may decrease dramatically.

Incineration and mixing

- Quality and property of the final product is highly dependent on the composition of sludge used.

Recommendations/ Further Research Required

- More studies are required on incorporation of deinking sludge on the properties of the final product.

TRL 4

Technology validated in lab

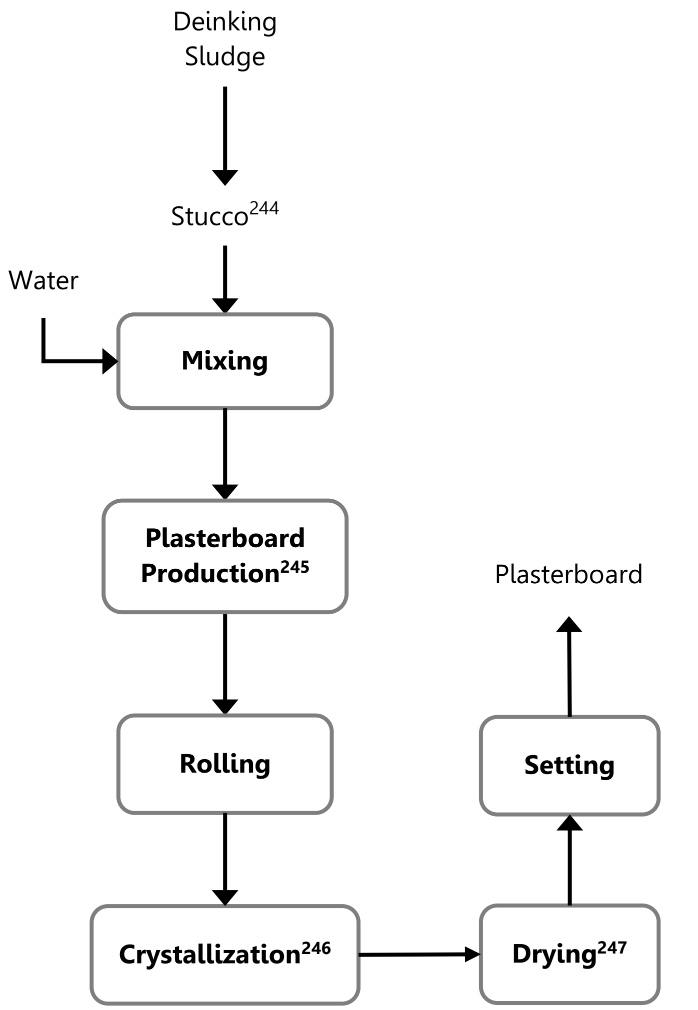
---

238 Azo Materials, *Ceramic Materials: What is the Importance of Fracture Toughness*, 2007.
239 See note 212, 140 – 142.
240 Deinking sludge is added with clay to produce ceramic materials.
241 Fired samples will be characterized by density, water absorption, shrinkage on firing, strength, hardness and fracture toughness measurements.

PLASTERBOARD ADDITIVE[242, 243]

Recovery (Thermal)

Process Description



WAC

- Not specified

Current Application

- Laboratory-scale study, where method has been patented.

Advantages

- Paper pulp can also be added to plaster to improve the tensile strength of the core.

Limitations

- Though the fibre proportion could be useful at strength improvement, it is possibly harmful for the fire-resistance of the plaster.

Recommendations/ Further Research Required

- Cellulose fibre content of different paper sludge from different stages on the mechanical properties of fibre cellulose composite should be further studied.

T R L 4

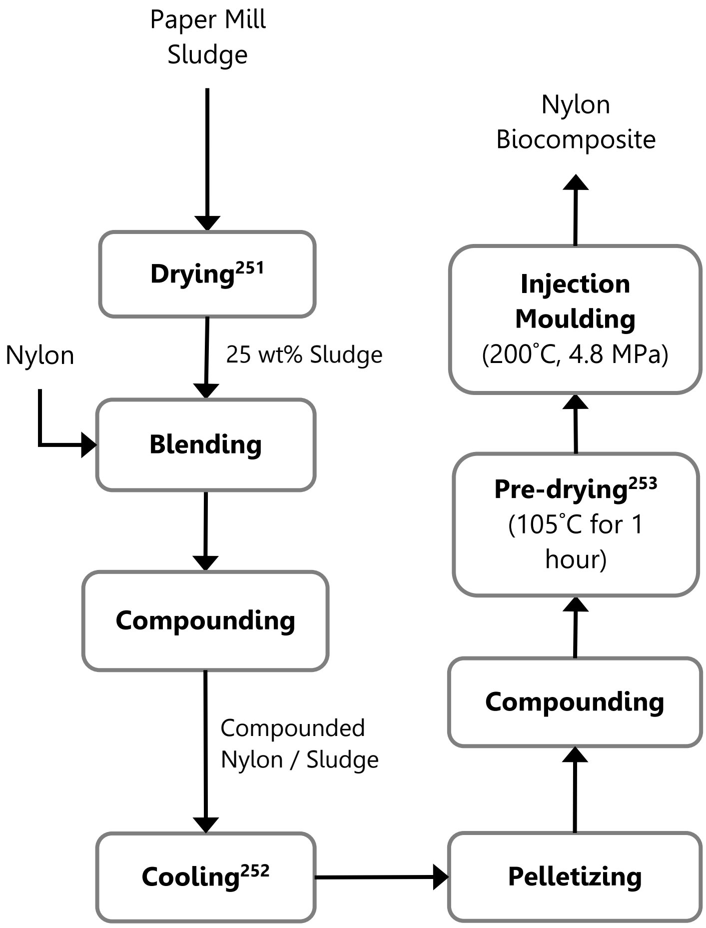
Technology validated in lab

[242] See note 212, 143 – 144.
[243] NWTT, *How to Fit Plasterboard*, 2023.
[244] Deinking sludge will be added at a consistency of 5-7 wt% to stucco.
[245] Stucco mixed with a stoichiometric quantity of water will then be poured onto a moving sheet of paper, where a second sheet will be glued to the upturned paper edge to produce plasterboard.
[246] The paper will form a sandwich, and the plaster will be rolled flat and allowed to set (crystallize) while moving down a long conveyor.
[247] The plasterboard will be dried with hot air after crystallization and allowed to set.

FILLER IN NYLON BIOCOMPOSITE PRODUCTION[248, 249, 250]

Recovery (Physical)

Process Description



Advantages

- Nylon has shown improvement in mechanical properties.

Limitations

- For higher melting temperature thermoplastics, e.g., Nylon 6, cellulosic fibres cannot increase the stiffness and strength of the composite despite their potential.

Recommendations/ Further Research Required

- Development of more economically viable feedstock which requires less energy consumption should be studied for commercial application.

WAC

- Low lipid content

Current Application

- Laboratory-scale study conducted in Canada.

TRL 4

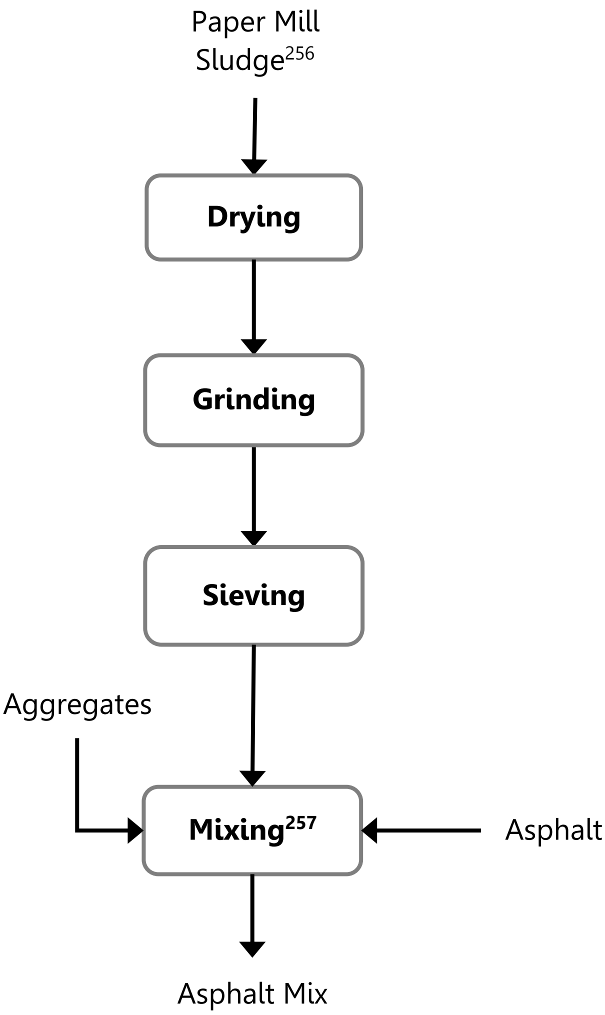
Technology validated in lab

[248] See note 212, 149.
[249] M E Manesh, *Utilisation of Pulp and Paper Mill Sludge as Filler in Nylon Biocomposite Production*, 2012.
[250] Material District, *Biocomposites*, 2020.
[251] Dried sludge (25 wt%) and nylon will be blended and then compounded.
[252] The compounded nylon/sludge will then be cooled down and pelletized.
[253] The pellets compounded will be pre-dried in an air circulated oven for 105˚C for 1 hour and then injection moulded at 200˚C, with injection pressure of 4.8 MPa and clamp pressure of 11.7 MPa.

PAVING AND FIBROUS ROAD SURFACING ADDITIVE[254, 255]

Recovery (Physical)

Process Description



WAC

- <7% moisture
- <20% ash content

Current Application

- Laboratory-scale study conducted in Canada.

Advantages

- Big savings in using paper mill sludge instead of imported paper additive in asphalt mix for road pavements.
- Able to achieve better properties for road surfacing materials.
- Able to reduce noise and provide enhanced binding, elasticity and durability to the pavements.

Limitations

- Drying properties of sludge is the limiting factor for sludge reuse.

Recommendations/ Further Research Required

- Still requires pilot-scale study to establish economic viability of the technology as well as the long-term performance of the asphalt mix in road pavement.

TRL 4

Technology validated in lab

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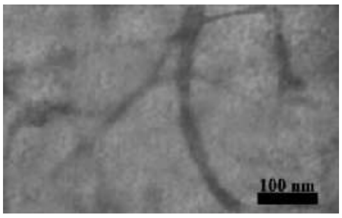
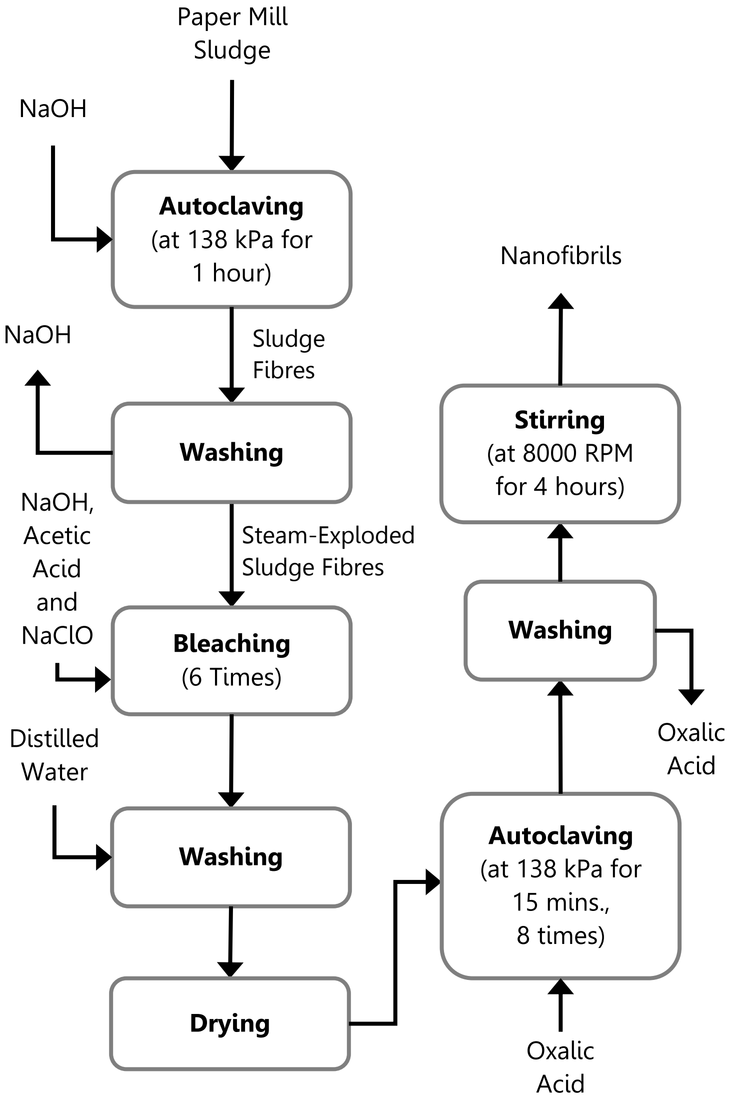
254 See note 212, 153 – 154.
255 Minergy Corporation Limited, *Hot Mix Asphalt*, 2011.
256 Paper mill sludge can be dried, ground and then sieved.
257 The resultant material will be mixed with aggregates and asphalt and then applied with heat, mixing and mechanical compaction in road pavements.

ACID TREATMENT TO EXTRACT NANOFIBRILS FOR NANOCOMPOSITES[258, 259]



Recovery (Chemical)

Process Description



WAC

- Low lignin, hemicellulose and other low molecular weight components

Current Application

- Laboratory-scale study

Advantages

- Sludge nanofibrils with the diameter below 20 nm were observed to be preserving the nanofibril structure after composite fabrication.
- Cellulose nanofibril in the prepared nanocomposites preserves the original crystalline structure of cellulose.
- Developed nanocellulose and its composites confirmed to be a very versatile material having the wide range of biomedical applications and biotechnological applications.

Limitations

- Expensive process to commercialize.

Recommendations/ Further Research Required

- Larger scale study is required for the extraction of nanofibrils and to establish economic viability.

TRL 4

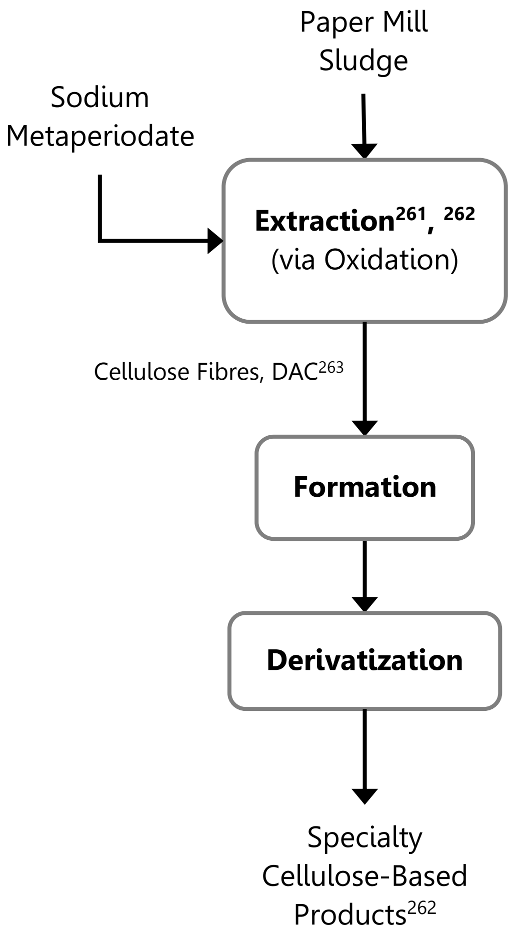
Technology validated in lab

[258] See note 212, 153.
[259] Leão *et al., Use of Primary Sludge from Pulp and Paper Mills for Nanocomposites*, 2015.

OXIDATION FOR EXTRACTION OF CELLULOSE FIBRES TO PRODUCE DERIVATIVES AND/OR VALUE-ADDED PRODUCTS[260, 261]

Recovery (Chemical)

Process Description

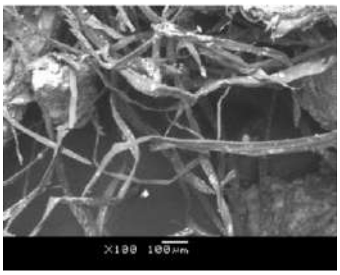


WAC

- High cellulose fibre content in paper mill sludge

Current Application

- Laboratory-scale study



Advantages

- High cellulose fiber content (50 – 55%) present in the paper mill sludge enables the sludge to be treated as a source of cellulose.

Limitations

- Reaction route of including the extraction, intermediate formation and derivatization of cellulose is dependent upon several major factors.

Recommendations/ Further Research Required

- Require finding the optimum conditions for the process.

T R L 4

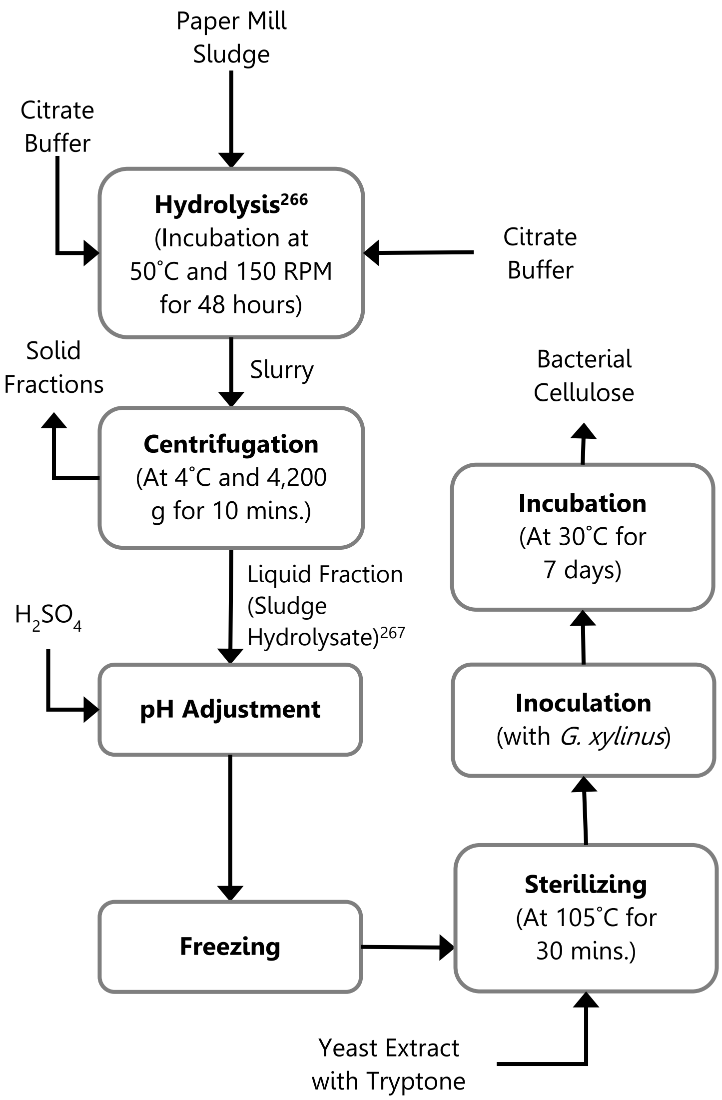
Technology validated in lab

[260] See note 212, 152 – 153.
[261] See note 226.
[262] The oxidation process activates the unreactive fibres for further derivatization by forming a biodegradable intermediate called dialdehyde cellulose (DAC)
[263] The DAC formed, which is highly reactive, can be further treated through crosslinking with substituent groups to form specialty cellulose-based products.

SEQUENTIAL FERMENTATION TO FORM BACTERIAL CELLULOSE AND ENZYMES[264, 265]

Recovery (Biological)

Process Description



Advantages

- Can be hydrolysed to sugars without any pre-treatment.
- Production of bacterial cellulose from paper sludge gives a cellulose polymer displaying superior properties compared to that produced from a glucose-based reference medium.

Limitations

- High cost of hydrolytic enzymes.

Recommendations/ Further Research Required

- Economic viability of hydrolytic enzymes shall be investigated.
- Conditioning of hydrolysates and optimization of the cultivation conditions, which are expected to result in higher volumetric yields, can be further studied.

WAC

- ≤5% lignin content

Current Application

- Laboratory-scale study

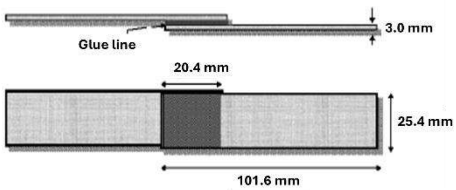
TRL 4

Technology validated in lab

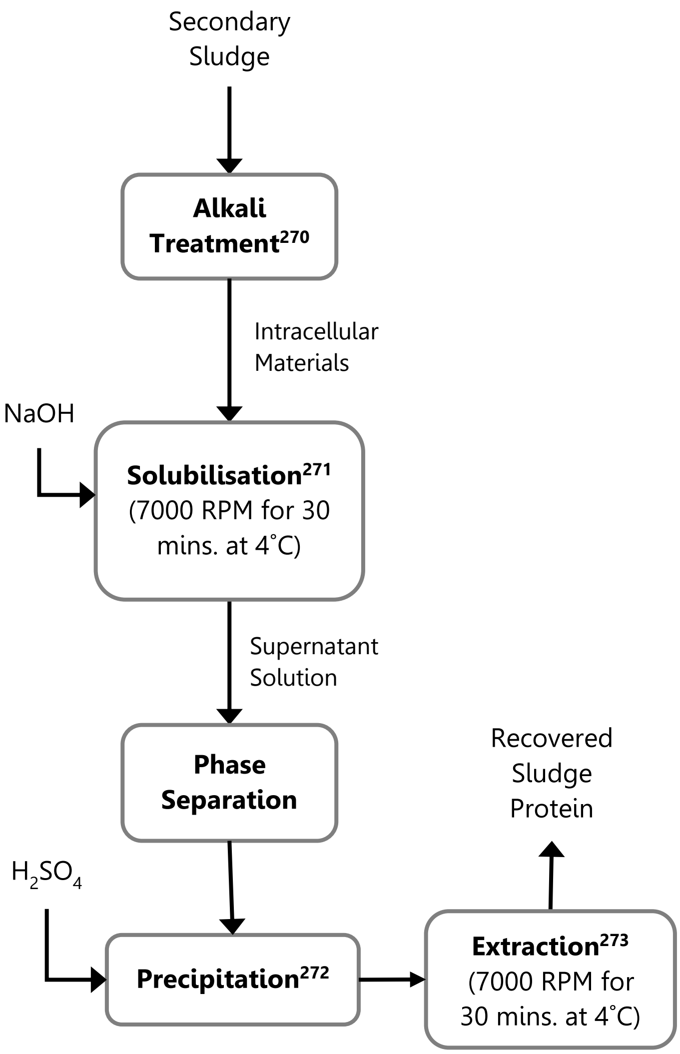
[264] See note 212, 151 – 152.
[265] Cavka *et al., Production of bacterial cellulose and enzyme from waste fiber sludge*, 2013.
[266] Hydrolysis of the fibre sludges will be performed enzymatically without any prior thermochemical pre-treatment.
[267] The sludge hydrolysate will be supplemented with yeast extract and tryptone in a flask to be autoclaved to sterilize the growth media.

WOOD ADHESIVE[268, 269]

Recovery (Physico-Chemical)



Process Description



Advantages

- Recovered sludge protein has significantly lower ash and lipid contents compared to untreated sludge, which is advantageous as it enhances adhesion properties.
- High process yield was achieved to extract protein through an alkaline cell-disruptive.

Limitations

- Limited knowledge pertaining to protein recovery from paper sludge and its characterization for usage as wood adhesive.

Recommendations/ Further Research Required

- Require further protein recovery from paper secondary sludge studies and its characterization.
- Explore opportunities in the hybrid formulations of sludge proteins with other high strength adhesives.

WAC

- Low ash content
- Low lipid content

Current Application

- Laboratory-scale study

T R L 4

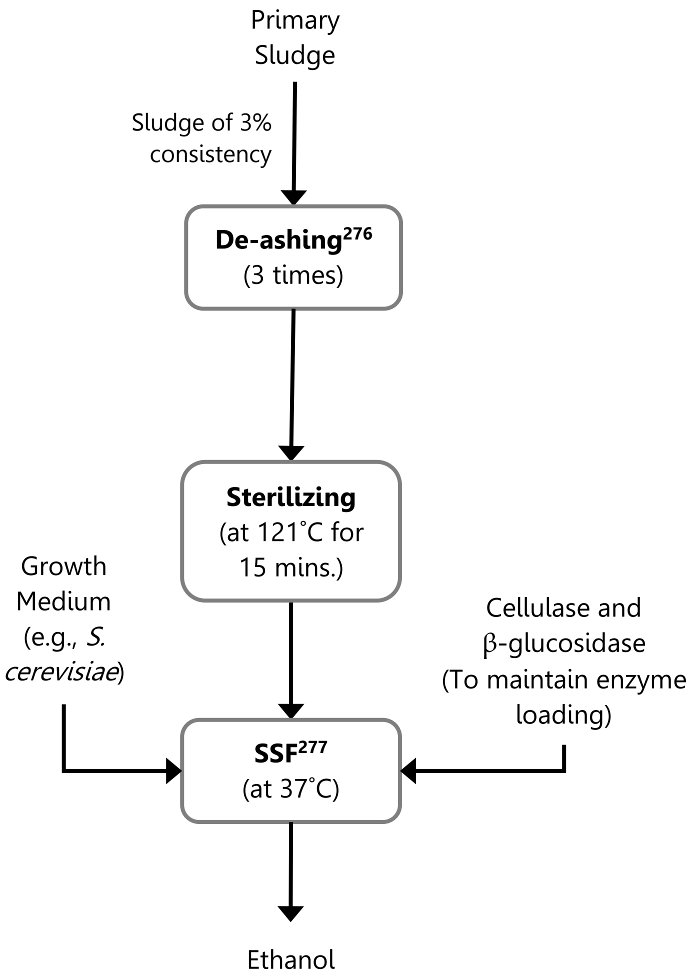
Technology validated in lab

[268] See note 212, 145 – 146.
[269] M Pervaiz and M Sain, *Protein Extraction from Secondary Sludge of Paper Mill Wastewater and Its Utilisation as a Wood Adhesive*, 2011.
[270] Secondary sludge will first be disintegrated using alkali treatment, releasing the intracellular materials into aqueous phase.
[271] pH of sludge will then be raised to 12 by adding NaOH while constantly stirring the sludge.
[272] The soluble protein will be precipitated out by lowering the pH of supernatant with H_2SO_4.
[273] Finally, the precipitates will be centrifuged at 7000 RPM for 30 minutes at 4˚C to obtain the recovered sludge protein in the pellet form, which can be used as wood adhesives.

SIMULTANEOUS SACCHARIFICATION AND FERMENTATION (SSF) TO PRODUCE ETHANOL[274, 275]

Recovery (Biological)

Process Description



WAC

- Low ash content sludge
- <21% w/v solid loading

Current Application

- Laboratory-scale study

Advantages

- Net gain in the overall process economics is expected from the de-ashing process.

Limitations

- Dense sludges with high solid loading require longer time for liquefaction, giving very low ethanol yield.
- Some fermentation medium may need to be sterilized to remove bacterial contaminants.
- High ash content in paper mill sludges limits the cellulose loading capacity in the bioreactor.

Recommendations/ Further Research Required

- Require further studies, such as de-ashing the paper mill sludge, to improve the bioconversion process, i.e., increasing ethanol yields.

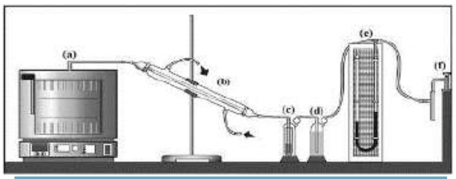
T R L 4

Technology validated in lab

---

274 See note 212, 109 – 115.
275 Kang *et al., Enhanced ethanol production from de-ashed paper sludge by simultaneous saccharification and fermentation and simultaneous saccharification and Co-fermentation*, 2011.
276 The de-ashing process will be conducted by mixing the resuspended sludge of 3% consistency at 300 RPM using a stirrer for 30 minutes with carbon dioxide bubbles flowing through two glass tubings, and putting through 100-mesh screen. The procedure will be repeated three times until the sludge mixture is thickened to about 45% consistency using a vacuum filter.
277 After sterilizing, the sludge samples will be added together with growth mediums (microorganisms such as *S. cerevisiae*) into a bioreactor, which will be operated in an incubator shaker at 37˚C with 150 RPM for fermentation.

SORBENT PRODUCTION VIA PYROLYSIS[278, 279, 280, 282, 281]



Recovery (Thermal)

Process Description

Dried[283] and Milled Primary Sludge[284]

Dried[283], Milled and Sieved Secondary Sludge[284]

Pyrolysis[285]
(at 800˚C for 150 mins.)

HCl

Acid Washing

Distilled Water

Ash and other inorganic

Washing[286]

Carbon

Drying[283]
(at 105˚C for 24 hours)

Carbon-based Absorbents

WAC

- Dried sludge

Current Application

- Laboratory-scale study

Advantages

- Pyrolysis allows for the recovery of 95-98% of the energy contained in dry sludge from the paper industry, which might result in significant improvements in its economic feasibility.
- Other useful by-products from pyrolysis includes a mixture of gaseous and liquid (bio-oil) fuels.

Limitations

- Sludge from different factories had implications in the properties of the carbon adsorbents produced, which might constitute in important drawback for the operation of centralized pyrolysis infrastructures.

Recommendations/ Further Research Required

- Research on new and sustainable systems for sludge pyrolysis, i.e., usage of microwave-assisted production to lower the energy requirement.
- A complete economic analysis of the production and implementation costs should be performed prior to industrialization.

T R L 4

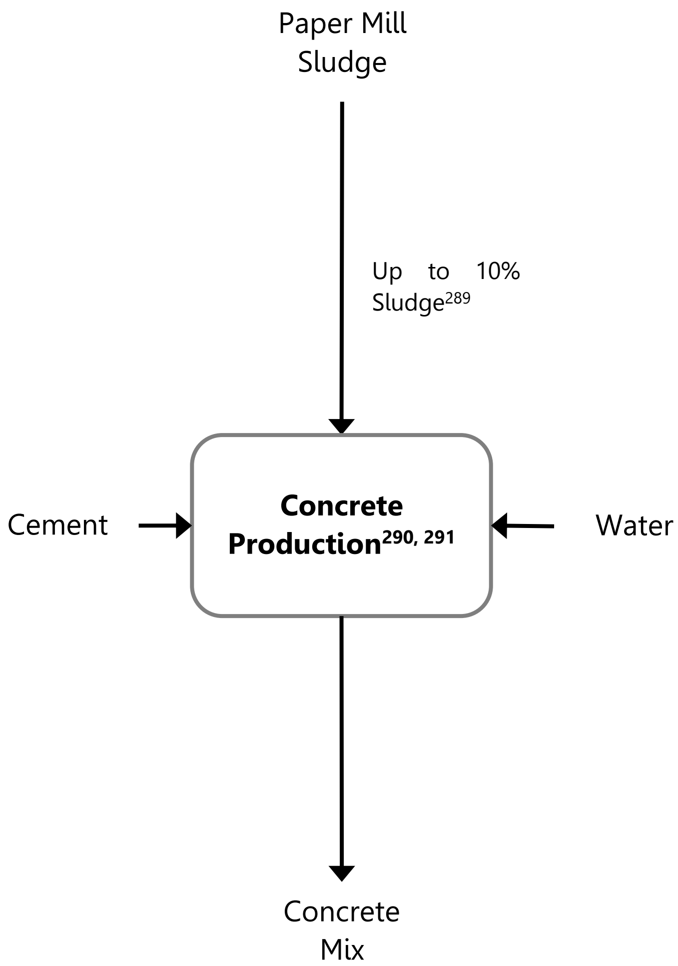
Technology validated in lab

[278] See note 212, 147 – 148.
[279] J Correia *et al.*, *Adsorbents made from textile scraps*, 2018.
[280] G Jaria *et al.*, *Sludge from paper mill effluent treatment as raw material to produce carbon adsorbents*, 2017.
[281] C J M Kok, *Patent CA1149657A*, 1983.
[282] See note 226.
[283] Primary and secondary sludges will be dried at room temperature, then followed by a 24-hour drying at 105˚C in the oven.
[284] Secondary sludge will be grinded and then sieved, where only 0.5-1.0mm fraction will be used, whereas for primary sludge, it will be milled without sieving.
[285] The samples will be pyrolyzed in a muffle, where the pyrolysis will be carried out under inert atmosphere (nitrogen flow) at 800˚C for 150 minutes. Pyrolyzed materials, e.g., carbon, will be washed with 1.2M HCl followed by distilled water until the washing solution reached neutral pH.
[286] The washing procedure is to remove ashes and other inorganic matter, to improve microporosity and surface area by unblocking obstructed pores.

CONCRETE PRODUCTION[287, 288]

Recovery (Physical)

Process Description



Advantages

- More sustainable option as it reduces the use of manufactured Portland cement clinker.
- Improves air quality while minimizing wastes.

Limitations

- Strength of concrete will decrease when percentage of paper mill sludge in the mixture increased.

Recommendations/ Further Research Required

- Studies on the compressive, splitting tensile and flexural strength shall be conducted to evaluate the mechanical properties and performance of the concrete formulations.

WAC

- Higher long, good-condition fiber content

Current Application

- Laboratory-scale study for construction purposes and tests were conducted.

T R L 6

Technology demonstrated in relevant environment

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[287] See note 212, 138 – 140.
[288] Designing Buildings, Concrete, 2023.
[289] Cement in concrete production can be replaced by paper mill sludge of up to 10% by weight for M-20 and M-30 mix.
[290] Adequate amount of sludge and water will be mixed, and concrete mixtures will be produced.
[291] A series of tests, such as compressive strength, splitting tensile-strength test and flexural strength, have to be conducted on the cast samples containing different formulations according to the Malaysian Standard, MS EN 12504:2013 Testing concrete in structures.

RAW MATERIAL FOR CEMENT MORTAR PRODUCTS MANUFACTURING[292, 293]

Recovery (Physical)

Process Description

Paper Mill Sludge

↓

Blending[294] ← Portland Cement

↓

Compressing
(0.08 – 0.12 MPa)

↓

Solidification
(Natural / Artificial)

↓

Cement Mortar Blocks[295, 296]

WAC

- Low moisture content
- Low organic matter content (cellulose)
- Low ash content

Current Application

- Pilot plant was established by overseas industry players, e.g., in Ukraine.

Advantages

- High heat protection.
- Enabled wall thickness to be decreased.
- Buildings made of the cement blocks are energy efficient.

Limitations

- Cellulose in the sludge may delay final setting time of the cement mortar mixture.
- Sludge proportion increases drying shrinkage and the volume of permeable voids in the final product.

Recommendations/ Further Research Required

- Studies to provide better workability and consistency, and freezing durability to the concrete.

T R L 7

System prototype demonstration in operational environment

---

[292] See note 212, 136.
[293] P Chhantyal, *The Advantages of using Nanoparticles in Cement Mortar*, 2020.
[294] Wet sludge will be blended with Portland cement without water.
[295] To prevent dried blocks from water absorption, its opened surface is recommended to be covered with repellent.
[296] A series of tests, such as compressive strength, splitting tensile-strength test and flexural strength, have to be conducted on the cast samples containing different formulations according to the Malaysian Standard, MS EN 12504:2013 Testing concrete in structures.

VERMICOMPOSTING[297, 298]

Recovery (Biological)

Process Description

Earthworms[299]
(e.g., *Lumbricus terrestris, Octolasian cyaneum,* or *Eisenia Andrei)*

Nitrogen Source (e.g., Yeast extract, rabbit manure, sewage sludge, or pig or hen slurries)

Mineralization of Paper Mill Sludge[300]

Water

Vermicompost

WAC

- C/N ratio of about 25

Current Application

- Pilot-scale study and field tests conducted by overseas industry players, e.g., Italy.

Advantages

- Low-cost technology system for processing of organic wastes.
- Vermicompost has desirable aesthetics, reduced levels of contaminants, is homogenous and tends to hold more nutrients over a longer period, without negatively impacting the environment.

Limitations

- Difficult degradation of the structural polysaccharides and the low nitrogen content of the sludge.
- Not much published information available on vermicomposting of paper mill sludges.
- Different earthworm species could respond differently to different sources of nitrogen.

Recommendations/ Further Research Required

- Extensive information and study are required on vermicomposting of paper mill sludges.

TRL 7

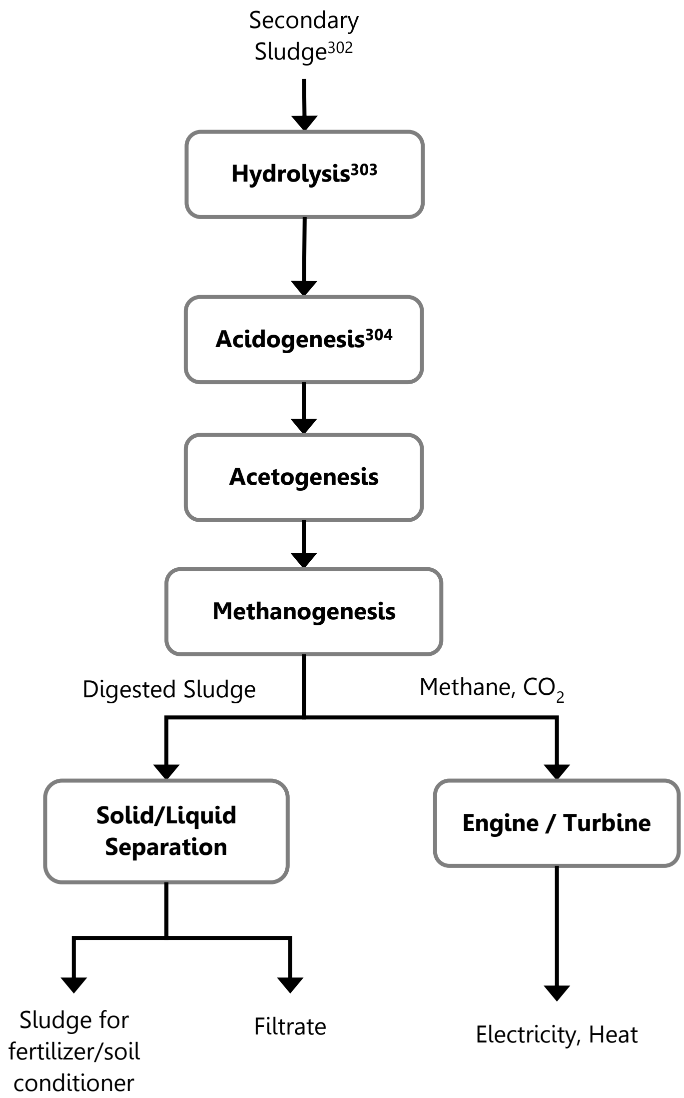
System prototype demonstration in operational environment

[297] See note 212, 94 – 98.
[298] Water Technology, *Paper mill sludge generates business in Finland*, 2018.
[299] Using earthworms to feed on the paper solids which can be supplemented with a nitrogen source.
[300] The presence of earthworms will help to increase the mineralization of organic matter, favouring the breakdown of structural polysaccharides and increase the humidification rate.

ANAEROBIC DIGESTION[301]

Recovery (Biological)

Process Description



WAC

- Low inorganic content

Current Application

- Pilot study has been conducted by overseas industry player.

Advantages

- Anaerobic digestion of paper mill sludges could reduce solid wastes by 30-70% with the benefit of energy recovery through methane production.
- More economical than traditional settling basin dredging and land disposal method.
- Chlorinated organic substances can be detoxified through reductive dichlorination by microbial consortia.

Limitations

- Not much information is available related to anaerobic digestion of deinking sludge.
- Long residence time of sludge in the anaerobic digestor (20-30 days).
- Aerobic post-treatment process is often required to further degrade compounds which are non-degradable anaerobically (e.g. resinous acids).
- High investment and operational costs.

Recommendations/ Further Research Required

- Requires development and establishment of pretreatment of sludge prior to anaerobic digestion to accelerate hydrolysis of sludge.

T R L 7

System prototype demonstration in operational environment

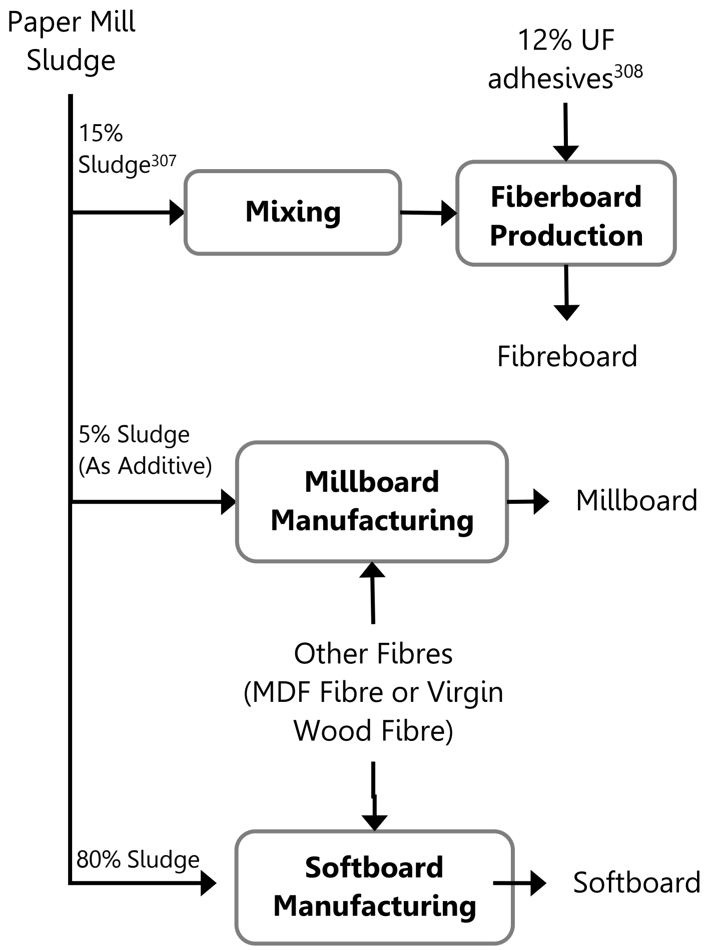
---

[301] See note 212, 122 – 126.
[302] Modern sludge preconditioning methods allow shortening of the residence time to only 7 days, where the pretreatment technologies include: ultrasound treatment, thermal treatment, ozone oxidation and mechanical degradation.
[303] In the first hydrolysis step, both solubilization of insoluble particulate matter and biological decomposition of organic polymers to monomer or dimmers will take place.
[304] Acidogenesis and acetogenesis follow in the second and third step, while in the fourth and final step, methane and carbon dioxide will be produced by methanogenic bacteria.

FIBREBOARD, MILLBOARD OR SOFTBOARD PRODUCTION[305, 306]

Recovery (Physical)

Process Description



Advantages

- Reduces usage of other fibres needed in fibreboard, millboard and softboard production, resulting in cheaper costs.
- Energy savings by using paper mill sludges.

Limitations

- Requires low ash content for production.
- Paper mill sludge is currently only able to substitute a portion of the raw material for fibreboard, millboard or softboard production.

Recommendations/ Further Research Required

<u>Fibreboard production</u>

- Board tests (ring crush test, Concora medium test, corrugated crush test) should be conducted to study the reusing of sludge in the paper and board industry.

<u>Millboard and softboard production</u>

- Studies should be further conducted to lower ash content below 10% for stronger and less dense final product.

Current Application

<u>Fibreboard production</u>

- Practiced by industry player overseas, e.g., Quebec, Canada, Turkey.

<u>Millboard and softboard production</u>

- Test trials has been conducted by overseas industry player, e.g., UK.

WAC

<u>Fibreboard production</u>

- 6 – 9.5% moisture content
- ≤ 35% proportion of fines

<u>Millboard production</u>

- High fibre content
- <10% ash content

<u>Softboard production</u>

- <10% ash content
- High fibre content

<u>Fibreboard Production</u>

TRL 9

Actual system proven in operational environment

<u>Millboard & Softboard Production</u>

TRL 6

Technology demonstrated in relevant environment

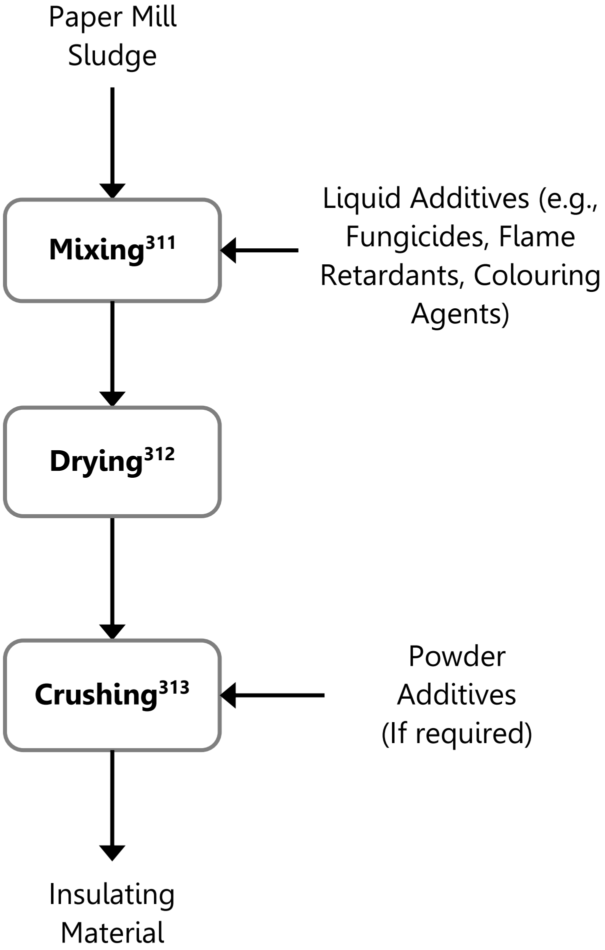
---

[305] See note 212, 127 – 130.
[306] European Panel Federation, *Softboard*, 2018.
[307] 15% paper sludge will be mixed with wood particles for fibreboard production.
[308] Boards are produced with 12% urea-formaldehyde (UF) adhesives.

RAW MATERIAL FOR INSULATING MATERIAL PRODUCTION[309, 310]

Recovery (Physical)

Process Description



WAC

- Long fibre sludges
- Low inorganic content
- > 60% moisture content

Current Application

- Utilization of paper mill sludge for production of construction and insulation boards has been long discussed and researched.

Advantages

- Usage of paper mill sludge as heat insulation material is comparable to other market insulation materials, as the thermal conductivity factor is lower than 0.055 W/m^2K.

Limitations

- Presence of inorganic content decreases insulating properties of the material being produced.

Recommendations/ Further Research Required

- Further research is required before implementation.

TRL 8

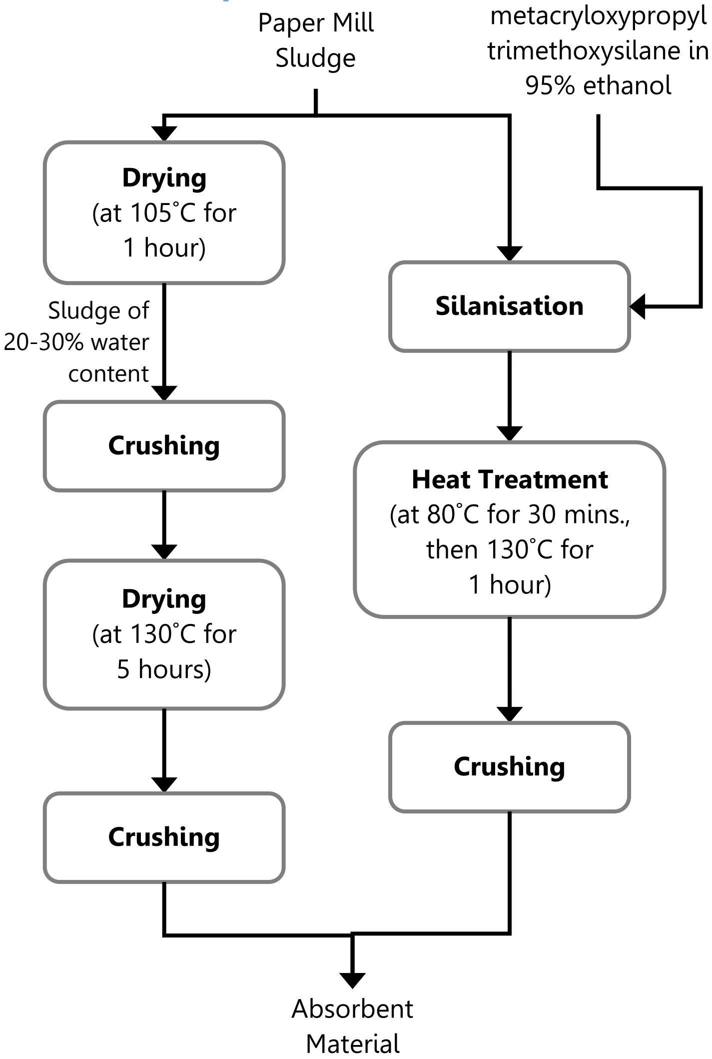
System complete and qualified

[309] See note 212, 144 – 145.
[310] Indiamart, *Acoustic Insulation Board*, 2023.
[311] Paper mill sludge will be mixed in a silo where liquid additives are added, if required.
[312] The mixture will then be sent for drying process to a drying machine.
[313] After drying, the mixture will be hammered in a crusher until the shape is flake-like.

CONVERSION OF PAPER MILL SLUDGE TO ABSORBENT (CAPS) PROCESS[314, 315, 316, 317]

Recovery (Physico-Chemical)

Process Description



WAC

- <70% ash content
- <10% moisture level
- Preferably >52% cellulose fibers

Current Application

- In market-uptake phase overseas

Advantages

- Prepared high efficiency absorbent absorbs more than 99% of the initial quantity of hydrophobic substance on the water surface in less than 60s, more efficient than most comparable natural and artificial absorbents available on the market.
- Product is a combustible material, especially when soaked with hydrocarbons; hence if incinerated under controlled conditions, the material will be vitrified and can be used as an inert absorbent for hard surface cleaning.

Limitations

- If absorbent material contains less than 52% cellulose fibers, it must be packed in a pad or cylinder shape to enable flotation.

Recommendations/ Further Research Required

- Mechanical treatment must be considered carefully to assure the optimum ratio between surface area and accessibility to obtain the maximum absorbency of the absorbent.

TRL 8

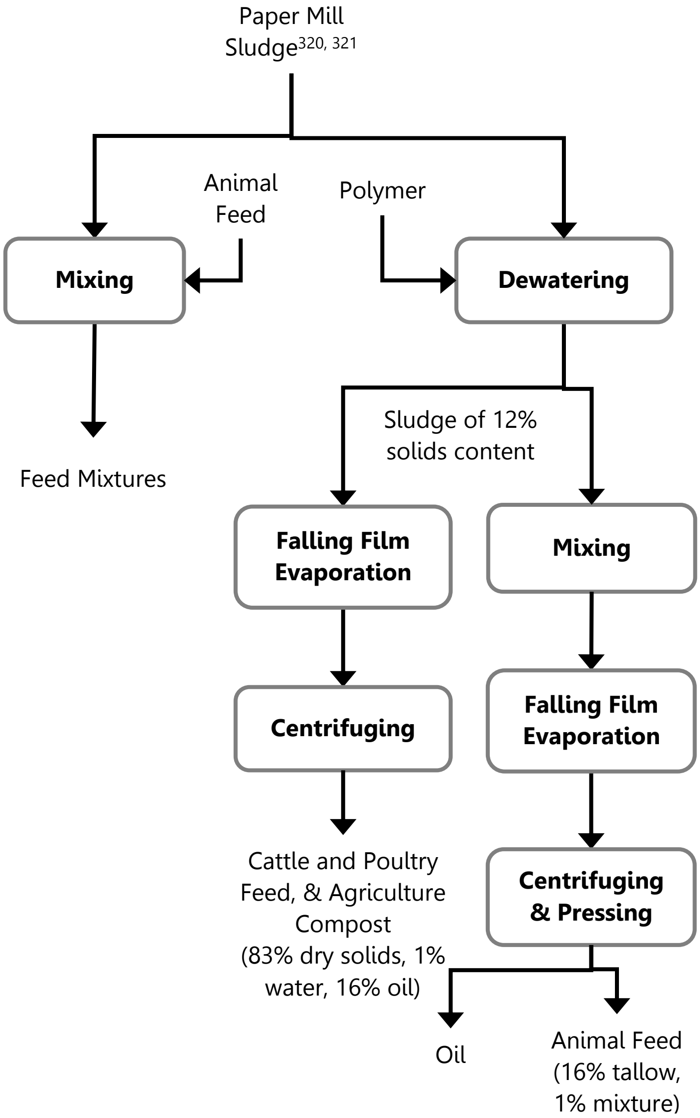
System complete and qualified

314 See note 212, 147 – 148.
315 See note 226.
316 See note 280.
317 See note 281.

ANIMAL FEED PRODUCTION[318, 319]

Reuse & Recovery (Physical)

Process Description



Advantages

- Contains promising substrates for single cell protein production.

Limitations

General

- Digestibility of cellulosic component in sludges is impaired by the presence of lignin and mineral matter.
- Overall yield to convert paper mill sludge's cellulosic components to single cell protein is low.

Biological conversion

- Capital and operating costs are substantial, and unless a market can be found for the product, the process seems to have limited application in the pulp and paper industry.

Recommendations/ Further Research Required

- Requires higher market acceptance and improvements in better palatability of the feed for wider application.

Current Application

Direct incorporation

- Laboratory-scale study and research in the early 1970s.

Mechanical conversion

- Practiced by industry players overseas, e.g., USA, though acceptance of these products is low.

WAC

- Low ash content
- Low lignin content

Direct Incorporation

T R L 4

Technology validated in lab

Mechanical Conversion

T R L 9

Actual system proven in operational environment

[318] See note 212, 115 – 116.
[319] Aqua Tech, *Boost for Animal Feed from Wastewater Tech*, 2021.
[320] Paper mill sludge, which contains carbohydrates (primarily in the form of cellulose and other nutrients present) will be added to feed mixtures.
[321] Secondary sludge can be mechanically dewatered to 12% solids by feeding a mixture of sludge and oil to specifically designed, multiple effect falling film evapourators.

SORBENT PRODUCTION VIA KAOFIN PROCESS[322, 323, 324, 325]

Recovery (Physical)

Process Description

Paper Mill Sludge

↓

Evaporation

↓ Sludge Pellets[326]

Drying (at 100-150˚C)

↓

Oil Absorbent Material

WAC

- Preferably 55-65% water by weight

Current Application

- Practiced by overseas industry players, e.g., International Absorbent Inc., Thermo Fibregen.

Advantages

- Cheap and efficient natural material for sorbent material.

Limitations

- If water content of sludge is too low, compression and extrusion of the mass into pellets requires excessive squeezing pressure, which will result in temperature rise and the surface properties will be adversely affected.
- If the water content is too high, the pellets obtained from the mass possess reduced structural strength and tend to crumble upon storage.

Recommendations/ Further Research Required

- Bulk density of the pellets should be further studied so necessary adjustments can be make for it to stay below 1 for easy removal from water.

T R L 9

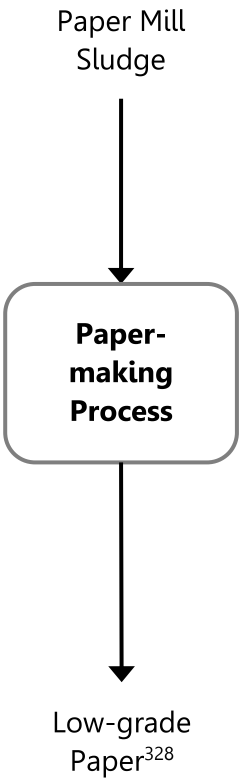
Actual system proven in operational environment

322 See note 226.
323 See note 280.
324 See note 281.
325 See note 314.
326 The sludge will be evapourated into pellets and dried at temperatures ranging from 100 to 150˚C to form an oil absorbent material.

PRODUCE LOW-GRADE PAPER[327]

Recovery (Physical)

Process Description



Advantages

- Able to cut down raw material costs.

Limitations

- Sludge that contains too much fines could produce easily torn paper with very low quality.

Recommendations / Further Research Required

- Further research is required before implementation.

WAC

- Low fines content

Current Application

- Practiced by local industry players, e.g., GS Paperboard & Packaging

TRL 9

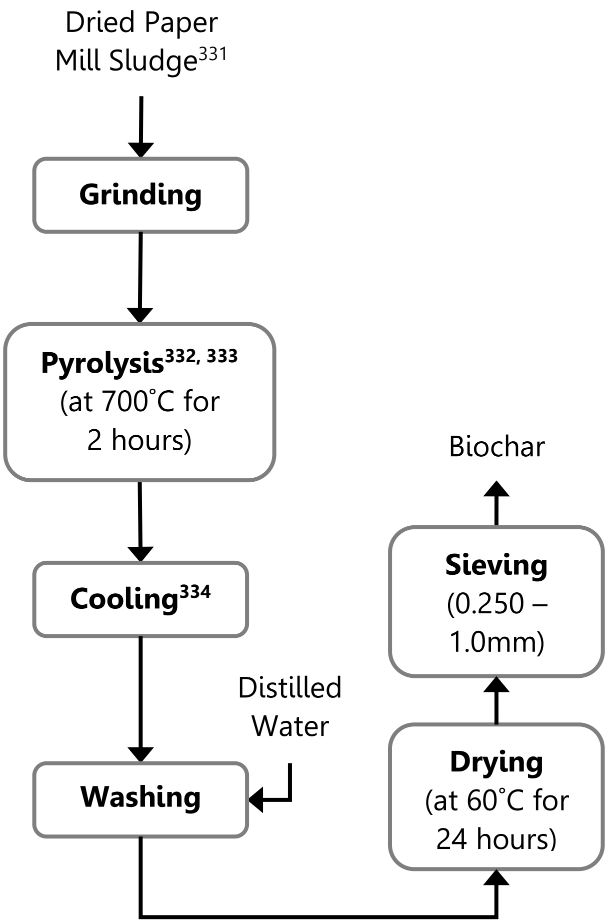
Actual system proven in operational environment

[327] See note 217.
[328] Sludge (containing long and short fibre) will be recycled into the paper-making process to produce low-grade paper.

PYROLYSIS FOR THE PRODUCTION OF FEEDSTOCK FOR PRODUCING BIOCHAR[329, 330]

Recovery (Physical)

Process Description



WAC

- Low chlorine content

Current Application

- Practiced by industry players overseas, e.g., USA, Italy.

Advantages

- Biochar application possesses potential for enhancing soil fertility.
- Thermal processing can destroy contaminants.
- Reduce potent GHG emissions.
- Slow pyrolysis can potentially achieve benefits of enhanced plant growth and soil quality.
- Leaching potential of heavy metals decreased after pyrolysis.

Limitations

- Not much information is available on pyrolysis of paper sludge waste and evaluation of its pyrolysis products.
- Caution should be exercised with the flammability of the product.
- If chlorine is used in paper production process (i.e., for whitening), this could be a potential source of dioxins and furans, which should be monitored.

Recommendations / Further Research Required

- Further research is needed before the benefits across a wide range of soil types and crops are determined.
- Possible contaminants in paper sludge should be assessed prior to each application.

TRL 9

Actual system proven in operational environment

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329 See note 212, 118 – 122.
330 Chalker-Scott, *Biochar: a gardener's primer*, 2014.
331 Paper mill sludge will be dried under sunlight for 3 days then oven dried at 70˚C for 48 hours.
332 Dried paper sludge samples will then be ground to particle size of 0.5mm – 1.25mm, then further pyrolyzed at 700˚C for 2 hours.
333 Optimum synthesis conditions for paper sludge pyrolysis would depend upon the composition and moisture content in the dried paper sludge as well as the time-temperature profile.
334 The biochar will be allowed to cool at room temperature under the flow of nitrogen gas.

FIBRE RECOVERY VIA SCREENING[335, 336]

Recovery (Physical)

Process Description

Primary Sludge[337]

↓

Cleaning[338] → Grit, inks and lightweight contaminants

↓

Screening → Short fibres

↓

Long fibres[339]

WAC

- Sludge with at least 40% of the matrix consisting of reusable fibre (e.g., white paper and primary sludge)

Current Application

- Practiced by local industry players.
- Practiced by industry players overseas, e.g., Prime Fibre Inc.

Advantages

- Overall economics of the recovery system can be improved by further developments relative to the addition of filler recovery processes.

Limitations

- Reuse of fibre from virgin fibre sludges resulted in increased pitch deposition on mill equipment.
- Minimum level for economic viability is 40% recoverable level.
- Product may contain unacceptably high dirt levels which will attribute to the sludge additions.

Recommendations/ Further Research Required

- Further research is required before implementation.

TRL 9

Actual system proven in operational environment

335 See note 212, 102 – 104.
336 See note 217.
337 In most cases, primary sludges will be cleaned and screened to separate the usable long fibres from other sludge components.
338 In the cleaning stage, the sludge will be removed of grit, inks and lightweight contaminants.
339 This will be followed by fibre recovery in a filter system.

PROCESSED INTO MOULDED PULP PRODUCTS, E.G., EGG TRAYS[340, 341, 342]

Recovery (Physical)

Process Description

Paper Mill Sludge

↓

Moulding[343] → Water (Removed by vacuum)

↓

Drying → Short fibres

↓

Moulded Pulp Products

WAC

- ≤ 10% ash content

Current Application

- Practiced by local industry players.
- Practiced by industry players overseas, e.g., West Fraser Timber's Alberta Newsprint Company

Advantages

- Technology has been around long enough that new techniques for producing smooth surfaces, precise shapes and dimensions have been developed, which is known as the Thermoforming process.

Limitations

- No further information of the manufacturing of paper mill sludge into moulding egg cartons or more specific characterization of the sludge was found.

Recommendations/ Further Research Required

- Further research is required before implementation.

T R L 9

Actual system proven in operational environment

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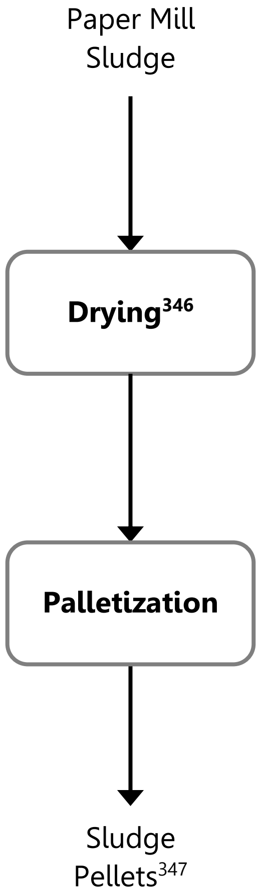
340 Asia Honour Paper, 2023.
341 See note 212, 130 – 131.
342 Time Business News, *Sales of U.S. Moulded Fiber Pulp Packaging Market will reach US$ 1.3 Bn*, 2022.
343 Pulp will be formed on a mould, where water will be partially removed by vacuum to form the shape after which the product is dried in an oven.

PELLETIZATION FOR VOLUME REDUCTION, ODOUR CONTROL, RECOVERY OF FUEL VALUE AND BY-PRODUCT APPLICATIONS[344, 345]

Recovery (Physical)

Process Description



WAC

- Dewatered sludge

Current Application

- Practiced by industry player overseas, e.g., USA.

Advantages

- Significant cost savings may occur through combustion of sludge pellets for energy generation.
- Pellets used as pesticide carrier materials has the advantage of being dust-free.

Limitations

- Production of sludge pellets to be used as by-product alternatives may induce high initial capital costs, have distribution and marketing issues, and incompatibility with company business strategies.

Recommendations/ Further Research Required

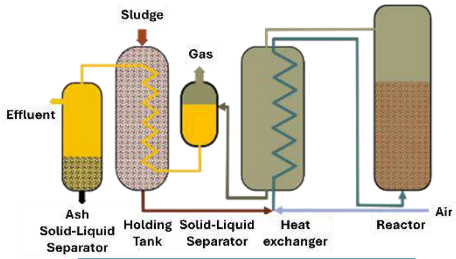
- Regulatory agencies are required to evaluate alternative fuels for by-products of combustion before widespread use of the fuel.

T R L 9

Actual system proven in operational environment

344 See note 212, 117 – 118.
345 P Undurraga *et al.*, *Pelletized paper mill waste promotes nutrient input and N mineralization in a degraded Alfisol*, 2017.
346 Dewatered sludge will be further dried and formed into pellets (Production of litter may involve sanitizing and deodourizing of sludge prior to drying).
347 These pellets can be used as alternative fuel, used as a balanced addition of nutrients required for plant growth, "carrier" material for garden pesticides, kitty litter, poultry litter, and large animal bedding.

WET AIR OXIDATION TO RECOVER RAW MATERIALS[348, 349, 350, 351]



Recovery (Thermal)

Process Description

Paper Mill Sludge

↓

Wet Air Oxidation[352, 353]

↓ Ash composed of inert materials (e.g., filler clay, titanium dioxide, and calcium carbonate)

Paper-Making Process

Advantages

- Sludge usage at 1:4 ratio indicates costs savings on wood and electricity.

Limitations

- Problems with calcium-sulphate and calcium-oxalate scale deposition.
- Demonstrated some problems with low brightness of the recovered filler.
- May have odour problems.

Recommendations/ Further Research Required

- Further research is required before implementation.

WAC

- COD load 10 – 80 kg/m^3

Current Application

- Practiced by industry players overseas, e.g., Turkey, USA.

TRL 9

Actual system proven in operational environment

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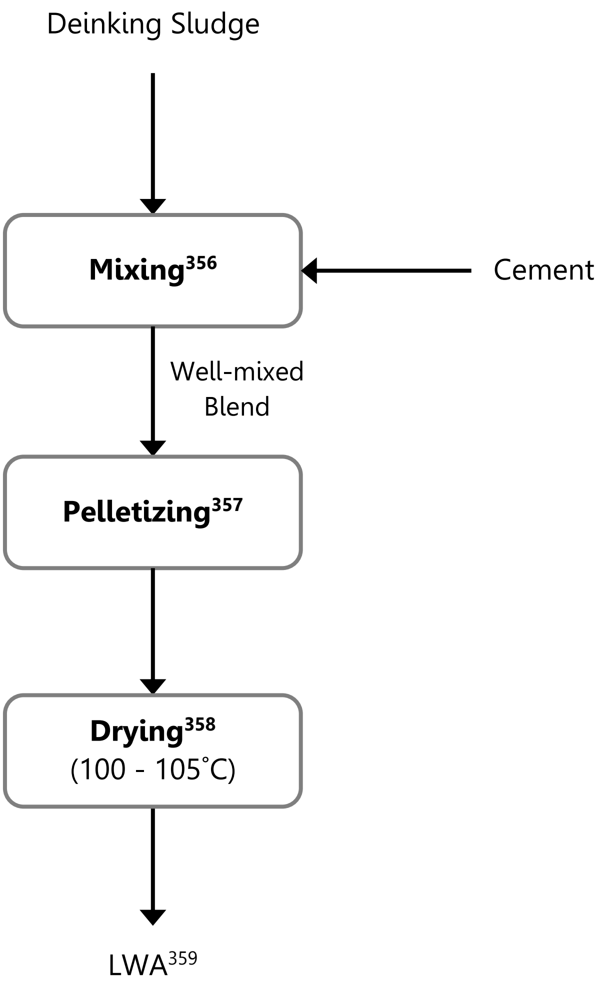
348 See note 212, 50 – 53.
349 Sludge Processing, *Wet (air) oxidation of sludge*, 2020.
350 L K Wang and N K Shammas, *1-Pressurized Ozonation*, 2007, 17.
351 P S Weigand and J P Unwin, *Alternative management of pulp and paper industry solid wastes*, 1994.
352 It is an oxidation reaction carried out in a liquid environment under high temperature and pressure. The typical conditions for wet air oxidation are 150 - 320˚C for temperature, 2 – 15 MPa for pressure, and 15 – 120 minutes for residence time.
353 Sludge volume will be reduced through oxidation of the organic fraction, yielding ash composed of inert materials.

LIGHTWEIGHT AGGREGATES (LWA) PRODUCTION[354, 355]

Recovery (Physical)

Process Description



WAC

- <30% ash content

Current Application

- Practiced by overseas industry players, e.g., Greengrove Corporation.

Advantages

- Incorporation of sludge has positive influence on LWA produced because even if the density decreases, the compressive strength still stays within acceptable limits.
- An alternative to disposing paper mill sludges in landfills.

Limitations

- Porosity of LWA produced is lower if mixing time is insufficient.

Recommendations/ Further Research Required

- Further research is required before implementation.

TRL 9

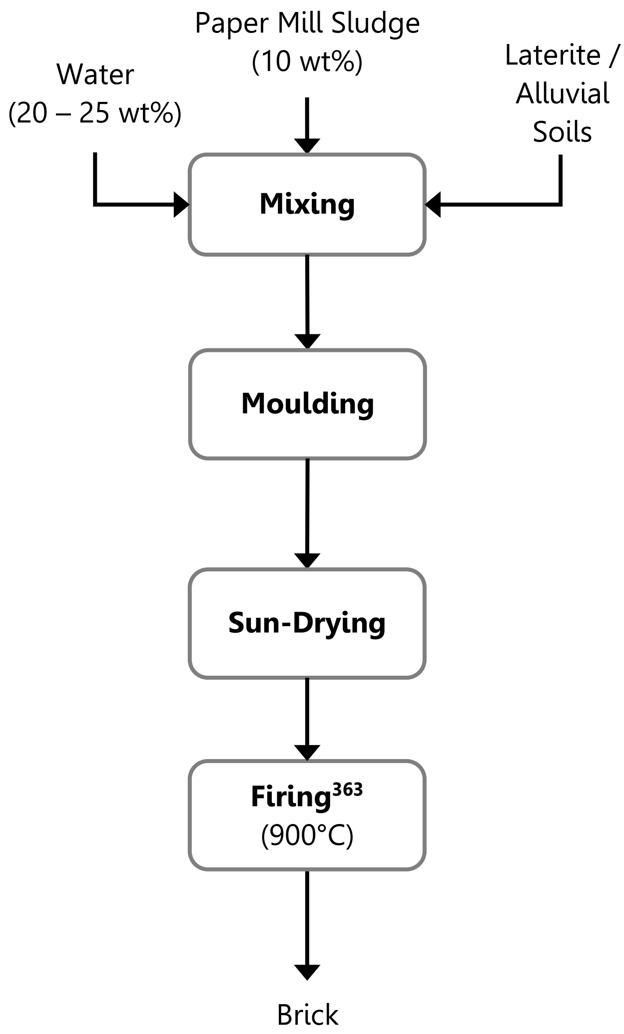
Actual system proven in operational environment

[354] See note 212, 142 – 143.
[355] Vin Civil World, *Lightweight Aggregate*, 2021.
[356] Deinking sludge will be mixed together with cement in a mixer.
[357] Well-mixed blend will then be sent to a pelletizing machine where granules will be produced.
[358] Last stage is the drying of the material produced at a temperature of 100 – 105˚C.
[359] Paper mill sludge added with ash can also produce LWA.

BRICK PRODUCTION[360, 361,362,]

Recovery (Physical)

Process Description



Advantages

- Paper mill sludge may contain fluxing agents (K_2O, Fe_2O_3, CaO, MgO and TiO_2), which aids in reducing firing temperature and possible saving of energy.

Limitations

- Maximum amount of paper mill sludge required to be added is 10 wt%. Any addition of paper mill sludge beyond this wt% results in excessively high water absorption values and low compressive strength.

WAC

- Paper mill sludge and clay should be grinded to particle size < 1 mm

Recommendations/ Further Research Required

- Further research is required before implementation.

Current Application

- Practiced by local and overseas industry players, e.g., India.

T R L 9

Actual system proven in operational environment

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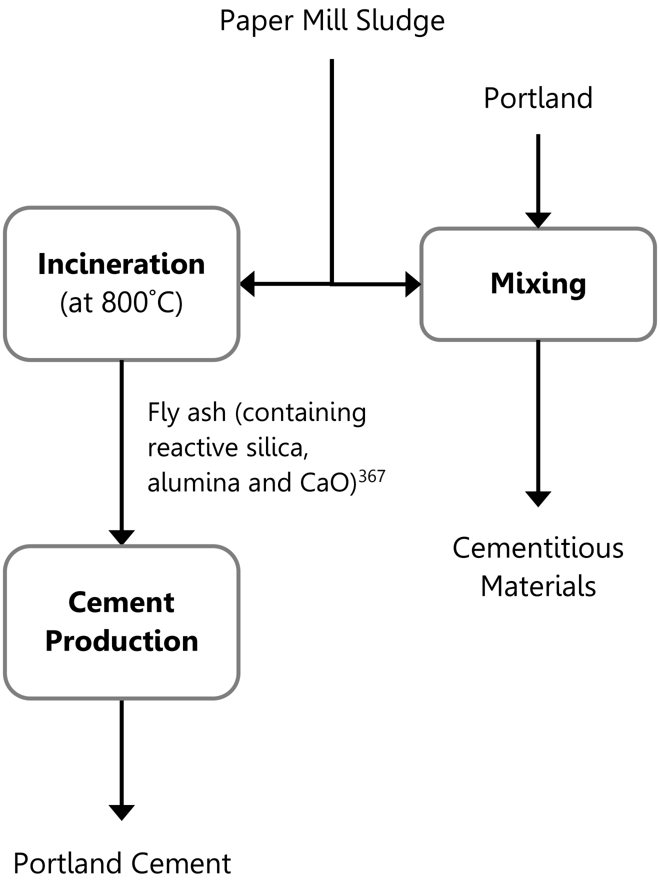
[360] G Goel and A S Kalamdhad, *An investigation on use of paper mill sludge in brick manufacturing*, 2017.
[361] In order to determine mineralogical, chemical, thermal and index properties, constituent materials of the brick (i.e., soils and paper mill sludge) will be thoroughly characterised prior to brick fabrication.
[362] Linear shrinkage, compression strength, water absorption, efflorescence, loss on ignition, apparent porosity and bulk density of the produced brick will need to be tested and determined prior to usage.
[363] Fired bricks will be kept in the furnace at this temperature for 1 h and then cool down to room temperature in the furnace by natural convection.

CEMENT AND CEMENTITIOUS PRODUCTS MANUFACTURING[364, 365, 366]

Recovery (Thermal)

Process Description



WAC

Cement production

- ≥ 85% solids content in sludge

Cementitious products manufacturing

- ≥ 35% solids content in sludge

Current Application

- Practiced by industry players overseas, e.g., Champion International's Hamilton plant in USA.

Advantages

Cement production

- Mixtures including Portland cement, ash, sand and sludge yielded a compressive strength comparable to conventional concrete and superior flexural strength.

Cementitious products manufacturing

- Increased durability and pumpability as well as reduced shrinkage-related cracking in products.

Limitations

Cement production

- One universal recipe for cement production does not exist.
- Deinking sludge may be more suitable due to its content.
- Due to low heating value of sludge, there may be some technological problems.

Cementitious products manufacturing

- Engineering properties of such material vary with the composition of the mix.

Recommendations/ Further Research Required

- Further research is required before implementation.

T R L 9

Actual system proven in operational environment

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364 See note 212, 133 – 135.
365 F Mohammadkazemi, *Papermaking Waste Sludge Fiber-Cement Composite Panel*, 2018.
366 C O Thomas, R C Thomas and K C Hover, *Wastepaper Fibers in Cementitious Composites*, 1987.
367 Resultant fly ash in the incineration process may contain reactive silica and alumina (in the form of metakaolin) as well as lime (CaO), which contributes chemically to the Portland cement ingredients in cement production. Energy content of sludge is utilized in the process when sludge is calcined together with ordinary raw meal.

Apart from the recovery of fibre as composite materials, thermal recovery of paper mill sludge is also one of the common practices. Paper mill sludges can be incinerated to obtain fly ash, which contains reactive silica, alumina and calcium oxide, that can be used in cement production. The typical chemical composition of cement can be referred in **Table 4-16** below:

Table 4-16: Typical Chemical Composition of Cement[368]

Compound	wt%
Lime, CaO	68.07
Silica, SiO_2	22.98
Aluminium Oxide, Al_2O_3	4.73
Iron (III) Oxide, Fe_2O_3	2.72
Magnesium Oxide, MgO	0.8
Potassium Oxide, K_2O	0.69

4.2.7 SW 205 – Waste Gypsum from Chemical Industries

Gypsum, which is chemically known as calcium sulphate dihydrate ($CaSO_4.2H_2O$), may be generated from various sources.[369] Mined gypsum is a common mineral found around the world in sedimentary rock formations, from which it is mined or quarried.[370] Another form of gypsum will be synthetic gypsum, which is mainly FGD gypsum from power stations and other byproducts from acid-neutralizing industrial processes.

FGD gypsum, which is short for flue gas desulphurisation gypsum, is produced when fossil-fuelled power plants FGD systems to remove sulphur dioxide from gas pollutants.[371] Through the scrubbing process, gas pollutants are fed through calcium carbonate to eliminate impurities and environmental concerns, and when the sulphur dioxide is removed, FGD gypsum forms as the byproduct.[372]

Apart from FGD, there are more than 50 other different types of synthetic gypsum, i.e., industrial wastes containing a high proportion of calcium sulphate, such as phosphogypsum, borogypsum and citrogypsum.[373] Some of the types of synthetic gypsum and their respective sources are as detailed in **Table 4-17.**

Table 4-17: Types of Synthetic Gypsum[374]

Name of Synthetic Gypsum	Process Resulting in Formation
Borogypsum	Boric acid production
Citrogypsum	Production of citric acid
Ferrogypsum	Lime treatment of iron vitriol solutions

368 See note 212, 134.
369 USEPA, *Agricultural Uses for Flue Gas Desulphurisation (FGD) Gypsum*, 2008.
370 ibid.
371 C Kozicki, *6 Facts about Synthetic Gypsum*, 2022.
372 ibid.
373 N Lushnikova and L Dvorkin, *Sustainability of gypsum products as a construction material*, 2016.
374 ibid.

Name of Synthetic Gypsum	Process Resulting in Formation
Fluorgypsum (fluoroanhydrite)	Sulphuric treatment of hydrofluoric acid
H-acid gypsum	Neutralization of free sulphuric acid collected during the formation of intermediate dyes
Hydrolysis gypsum	Hydrolysis of lignocelluloses by concentrated sulphuric acid
Phosphogypsum	Processing phosphate (apatite) ore into fertilizer with sulphuric acid
Red gypsum	Waste product from the titanium dioxide industry with considerable quantity of ferric flocs
Tartratogypsum	Production of tartaric acid
Titanogypsum	Titanium dioxide pigment production

Depending on the type of thermal equipment and parameters of dehydration, different calcium sulphate-based products formed; thus, we see gypsum often varying in composition, structure and properties.[375]

An example of gypsum waste from a chemical industry located in Johor has the following compositions (**Table 4-18**):

Table 4-18: Example of Waste Gypsum Composition[376]

Parameter	Unit	Composition
Calcium oxide, CaO	wt%	29.57
Sulphur trioxide, SO_3	wt%	29.56
Aluminium oxide, Al_2O_3	wt%	16.13
Silicon dioxide, SiO_2	wt%	8.86
Magnesium oxide, MgO	wt%	7.82
Iron (III) oxide, Fe_2O_3	wt%	4.88
Sodium oxide, Na_2O	wt%	2.39
Phosphorus pentoxide, P_2O_5	wt%	0.39
Manganese oxide, MnO	wt%	0.15
Potassium oxide, K_2O	wt%	0.11
Chlorine, Cl	mg/kg	418.0
Titanium dioxide, TiO_2	mg/kg	344.0
Zinc oxide, ZnO	mg/kg	111.0
Chromium (III) oxide, Cr_2O_3	mg/kg	56.0

4.2.7.1 Reuse Applications

There are several reuse applications available for waste gypsum, mostly due to its high calcium oxide, sulphur trioxide and aluminium oxide content. These components can be used as nutrient source for crops, to improve the soil's physical properties, or even as a precipitation agent or sulphurising agent for the treatment and recovery of other wastes (**Table 4-19**).

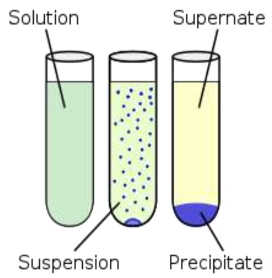
[375] See note 373.
[376] N J Abdul Hamid *et al.*, *Influence of Gypsum Waste Utilisation on Properties and Leachability of Fired Clay Brick*, 2021.

Table 4-19: Summary of Reuse Applications for SW 205 (Waste Gypsum from Chemical industries)

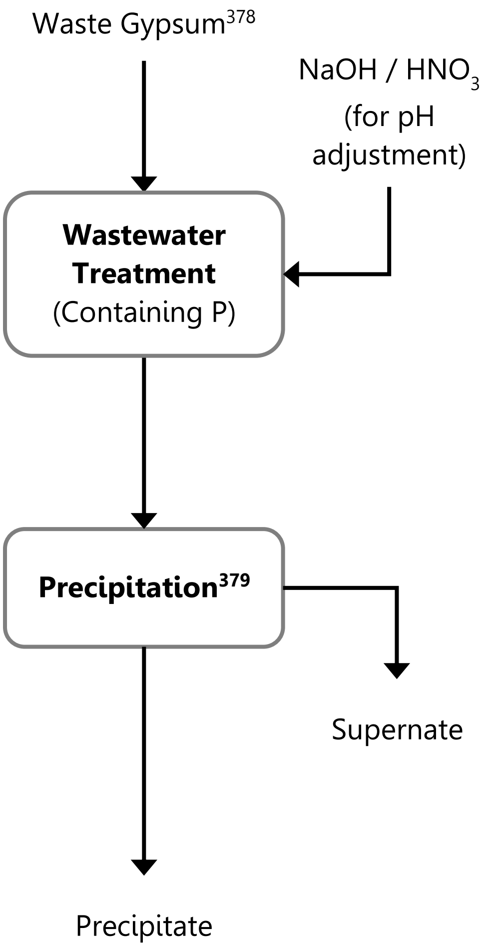
Reuse Applications	Technology Readiness Level (TRL)	Reference Page
Used as precipitation agent for phosphate recovery from wastewater	4 *Technology validated in lab*	4-98
Used as sulphurising agent for metal recovery from slag	4 *Technology validated in lab*	4-99
Reused for direct carbonation	7 *System prototype demonstration in operational environment*	4-100
Reused as soil conditioner	9 *Actual system proven in operational environment*	4-101
Mitigation of contaminant transport to surface water (prevention of nutrient loss)	9 *Actual system proven in operational environment*	4-102
Soil reclamation using waste gypsum	9 *Actual system proven in operational environment*	4-103

USED AS PRECIPITATION AGENT FOR PHOSPHATE RECOVERY FROM WASTEWATER[377]

Reuse



Process Description



WAC

- High calcium concentration

Current Application

- Laboratory-scale study

Advantages

- High phosphate removal or recovery (99%) achievable at optimum molar ratio ($[Ca^{2+}] : [PO_4^{3-}]$).

Limitations

- Other methods have to be developed for the treatment of wastewater in petrochemical industry as it also contains high concentrations of NH_4^+-N, which gypsum cannot treat.

Recommendations/ Further Research Required

- Further studies on large scale usage are required.

T R L 4

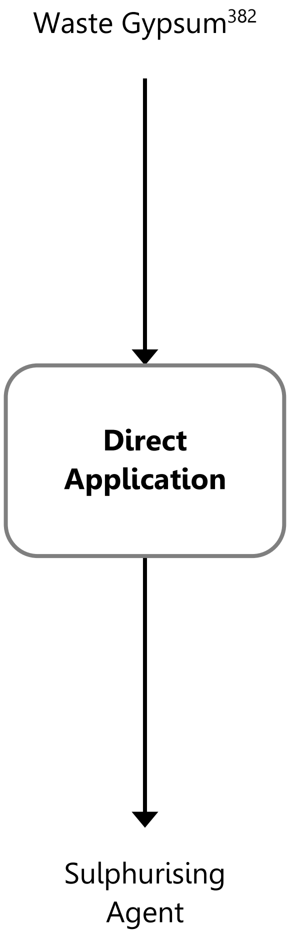
Technology validated in lab

[377] Warmadewanthi *et al.*, *Phosphate Recovery from Wastewater of Fertiliser Industries by Using Gypsum Waste*, 2017.
[378] Gypsum waste can be added directly to the wastewater containing phosphate.
[379] Precipitation will occur, where the solids will settle for 30 min, and a spectrophotometer will be used to measure its residual phosphate.

USED AS SULPHURISING AGENT FOR METAL RECOVERY FROM SLAG[380, 381]

Reuse

Process Description



Advantages

- Sulphurisation of metal from metal slag is proven feasible.

Limitations

- Amount of $CaSO_4$ contained in the gypsum sample is required to be determined so that the amount of slag to be added can be determined as well.
- Sulphurisation degree increased with decomposition temperature up until 1100˚C, then it will start decreasing due to the reduction.

Recommendations/ Further Research Required

- Further studies on the effect of the sulphurising agent and time can be conducted.

WAC

- Not specified

Current Application

- Laboratory-scale study

TRL 4

Technology validated in lab

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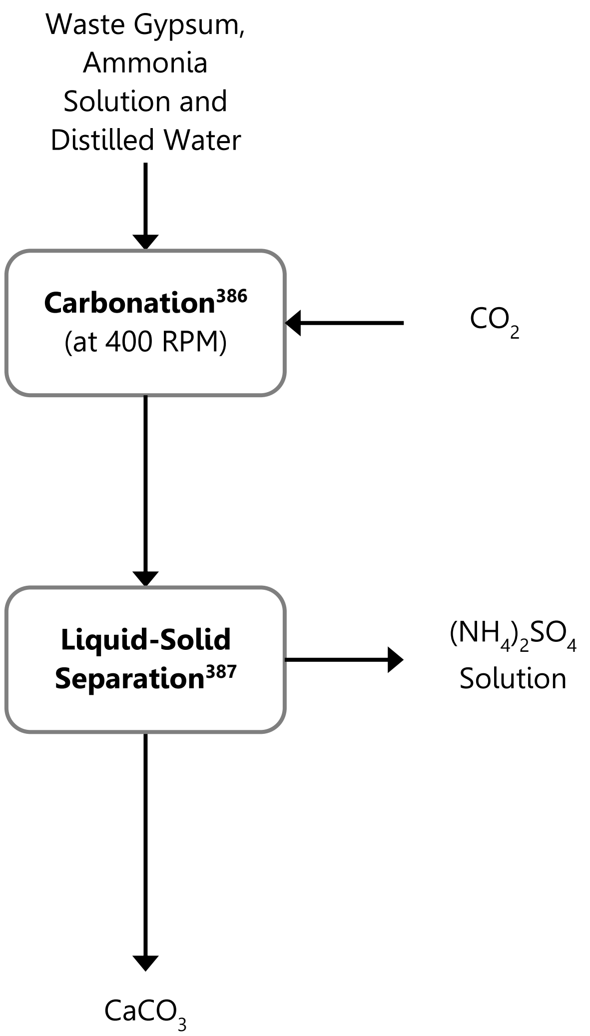
380 N Chauke, M Kalenga and W Nheta, *Use of waste gypsum from hydrometallurgical plant for the recovery of nickel from a nickel slag by sulfurization*, 2018.
381 JXSC, *Recycle Metal from Slag: The Recycling Process*, 2021.
382 Waste gypsum is used as the sulphurising agent to recover metal from metal slag, due to the major elements, calcium and sulphur.

REUSED FOR DIRECT CARBONATION[383, 384]

Reuse

Process Description[385]



WAC

- FGDG, RG and PG

Current Application

- Laboratory-scale study and field tests has been conducted overseas, e.g. in Korea

Advantages

- Main composition of waste gypsum is sulphate, which has high carbonation reactivity even at room temperature and atmospheric pressure.
- Calcium conversion efficiency can reach almost 100% at moderate conditions.

Limitations

- Serious concerns exist due to the existence of radionuclides and trace elements in gypsum.

Recommendations/ Further Research Required

- Process parameter optimization and equipment design for scale-up applications should be extensively investigated (particularly on the efficiency and sufficiency of mass or heat transfer).
- Investigation should also be done on the behaviour and distribution of heavy metals during the carbonation process.
- Life cycle assessment (LCA) technique should be introduced and evaluated for mineral carbonation and its optimization.

TRL 7

System prototype demonstration in operational environment

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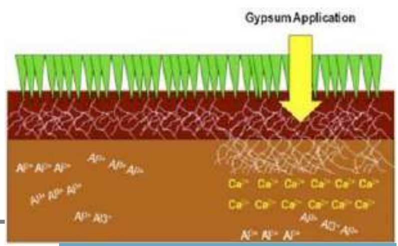
383 M G Lee *et al., Mineral carbonation of flue gas desulphurisation gypsum for CO2 sequestration*, 2012.
384 J Liu *et al., Separation mechanism of polyvinyl chloride and copper components from swollen electric cables by mechanical agitation*, 2019.
385 This method is suited for flue gas desulphurisation gypsum (FGDG), red gypsum (RG), and phosphogypsum (PG).
386 Waste gypsum slurry containing waste gypsum, ammonia solution and distilled water will be agitated in a carbonation reactor.
387 After 5 minutes, CO_2 gas will be continuously injected into the reactor at a predetermined flow rate. The slurry solution can then be separated into $CaCO_3$ (solid) and $(NH_4)_2SO_4$ solution.

REUSED AS SOIL CONDITIONER[388, 389, 390, 391]

Reuse



Process Description

Waste Gypsum[392]

↓

Direct Application

↓

Soil Conditioner

Advantages

- Able to remediate sodic (high sodium) soils.
- Reduction in nutrient and sediment movement to surface waters.
- An effective method of soil conservation and industrial material reuse.
- Gypsum is more readily soluble in water than other calcium-rich soil amendments.

Limitations

- Amount and types of trace materials found in gypsum can vary among different sources.

Recommendations/ Further Research Required

- The amendment material and soil conditions should be first assessed to determine compatibility and appropriate application rates.

WAC

- Depending on soil conditions

Current Application

- Practiced by local industry players.
- Practiced by overseas industry players, e.g., in USA.

T R L 9

Actual system proven in operational environment

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388 L Chen and W A Dick, *Gypsum as an agricultural amendment*, 2011.
389 See note 369.
390 Taiko Group, 2023.
391 Venator Asia, 2023.
392 Gypsum can be used as a nutrient source for crops (calcium and sulphur); as a conditioner to improve soil physical properties, i.e., soil conditioner was used to treat bris soil for plantation of Napier. Depending on the source, it may also provide essential micronutrients to plants. Gypsum exhibits water retention characteristics and can act as a sodium exchanger to reduce salinity of brackish water.

MITIGATION OF CONTAMINANT TRANSPORT TO SURFACE WATER (PREVENTION OF NUTRIENT LOSS)[393, 394]

Reuse

Process Description

Waste Gypsum[395]

↓

Direct Application

↓

Mitigation of contaminant transport[396]

WAC

- Depending on soil conditions

Current Application

- Practiced by overseas industry players, e.g., in USA.

Advantages

- Gypsum is particularly effective at reducing phosphorus losses.
- It can at least partially address many of the hydrological and chemical factors that influence phosphorus and other nutrient losses from agriculture to waterways.
- It has shown efficacy on phosphorus mitigation over a range of soil types and conditions.

Limitations

- Gypsum application in soil would seem less likely to make a significant difference for phosphorus losses where exchangeable calcium levels in soil are already high.
- Large losses of sulphate can occur from gypsum treated soils, which may affect some lakes and wetlands.
- Placement of gypsum may specifically be most effective in wide strips around runoff prone areas or in effluent treated or pugging prone paddocks.

Recommendations / Further Research Required

- Soil nutrient characteristics, and potential plant and animal uptake, of these and other constituents should be understood and considered before deciding whether to use any gypsum product.

T R L 9

Actual system proven in operational environment

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393 See note 369.

394 T A Jenkins and V Jenkins, *Use of Gypsum to reduce effluent and fertiliser nutrient losses to waterways*, 2020.

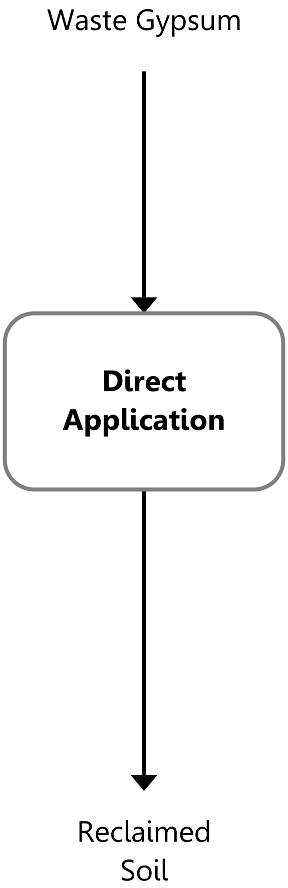
395 Waste gypsum application can reduce solubility of nutrients such as phosphorus in livestock and poultry manure and soils treated with manure. It converts readily soluble phosphorus to less-soluble forms, which can reduce the runoff of phosphorus into adjacent streams, lakes, or ground water.

396 Surface runoff losses may be reduced by improved water infiltration and aggregate stability. Release of calcium ions from gypsum may also impact on phosphate availability for environmental losses, which may be due to an increased in ionic strength of soil solutions causing increased mineral adsorption of phosphate.

SOIL RECLAMATION USING WASTE GYPSUM[397, 398, 399]

Reuse

Process Description



Advantages

- Addition of gypsum can reduce the pH of mud.
- Reduced ESP due to gypsum application in soil can enhance soil permeability.
- Low cost self-sustaining revegetation program.

Limitations

- Amount and types of trace materials found in gypsum can vary among different sources.
- Does not work for saline soils.

Recommendations/ Further Research Required

- Further investigation on the improvement of soil nutrient status.
- Further research on the leaching requirement prior to plant establishment to remove excess Na released following gypsum amendment.
- Further study to evaluate availability of Mn in amended soil.

WAC

- Depending on soil conditions

Current Application

- Practiced by local industry players.
- Practiced by overseas industry players, e.g., in USA.

TRL 9

Actual system proven in operational environment

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[397] J W C Wong and G E Ho, *Use of Waste Gypsum in the Revegetation on Red Mud Deposits: A Greenhouse Study*, 1993.
[398] A Hanay *et al.*, *Reclamation of Saline-Sodic Soils with Gypsum and MSW Compost*, 2013.
[399] Physical, chemical and biological properties of saline-sodic soils can be restored with treatment using gypsum and municipal solid waste compost sequentially.

4.2.7.2 Recovery Technologies

Reuse of waste gypsum is a very common practice as it is usually in ground powder form, which can be used readily as a substitute material or for other direct applications. Meanwhile, the types of recovery technologies for SW 205 include mostly physical recovery, with a mixture of chemical and thermal recovery methods, which is summarized in **Table 4-20**.

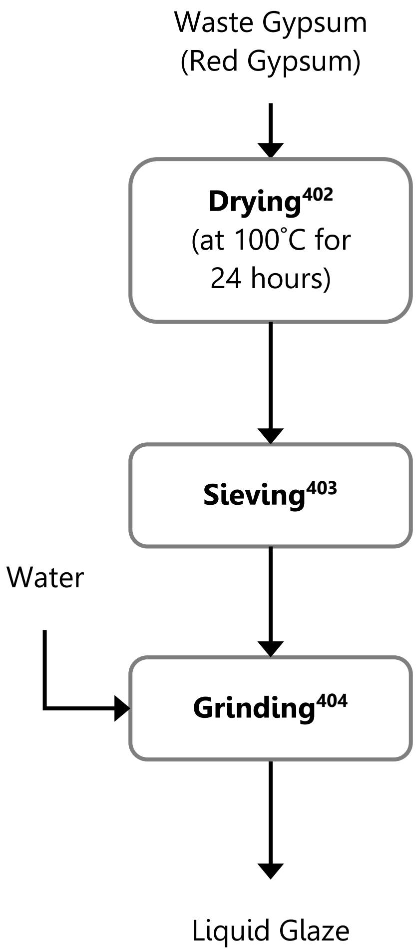
Table 4-20: Summary of Recovery Technologies for SW 205 (Waste Gypsum from Chemical Industries)

Recovery Technologies	Method	Technology Readiness Level (TRL)	Reference Page
Production of glaze from red gypsum waste	Physical	4 *Technology validated in lab*	4-105
Recovery process via reduction and PIPCo	Chemical	7 *System prototype demonstration in operational environment*	4-106
Reused for indirect carbonation	Chemical	7 *System prototype demonstration in operational environment*	4-107
Fired clay brick production	Physical	9 *Actual system proven in operational environment*	4-108
Concrete and cement applications	Physical	9 *Actual system proven in operational environment*	4-109
Wallboard products manufacturing	Thermal	9 *Actual system proven in operational environment*	4-110

PRODUCTION OF GLAZE FROM RED GYPSUM WASTE[400, 401]

Recovery (Physical)

Process Description



WAC

- Red gypsum

Current Application

- Laboratory-scale study

Advantages

- RG glazes are suitable to be used for glazing wall tiles and tablewares.
- Glazes produced from RG is stable under normal conditions since no crazing was observed at room temperature and pressure, and stable under acidic condition.

Limitations

- RG glaze may be less stable in alkaline, high pressure and temperature conditions.

Recommendations/ Further Research Required

- Further studies on large scale production are required.

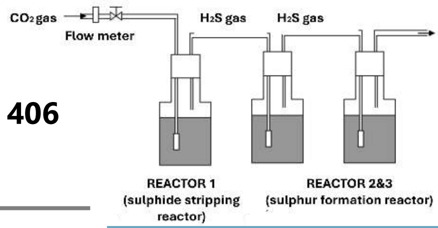
TRL 4

Technology validated in lab

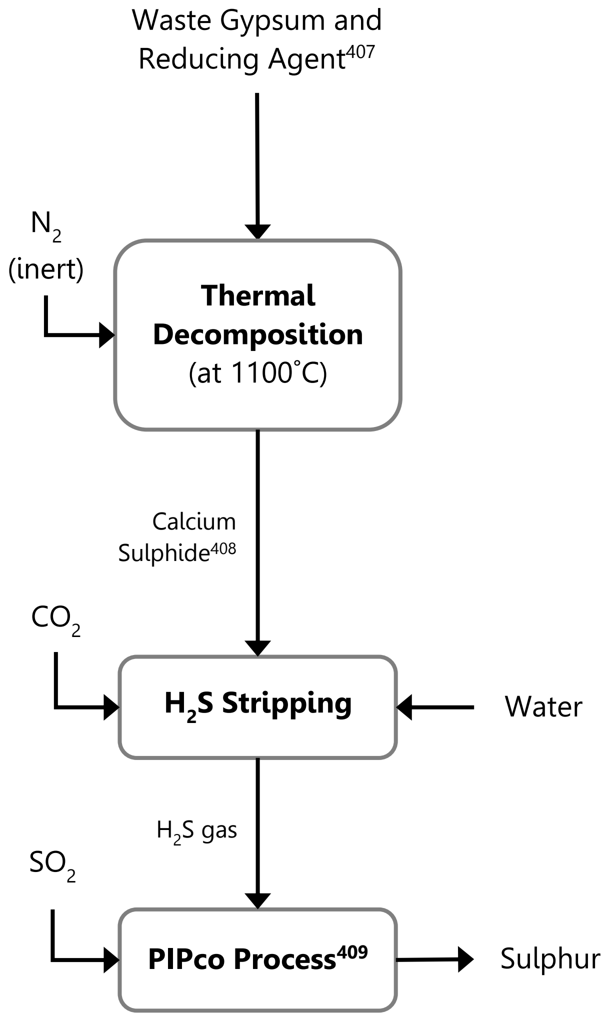
[400] R A Kamarudin and M S Zakaria, *The Utilisation of Red Gypsum Waste for Glazes*, 2007.
[401] IndiaMart, *Red Gypsum Granules*, 2023.
[402] Red gypsum (RG) waste will be first dried for 24 hours at 100°C, then grinded.
[403] Sieved red gypsum waste will then be placed in an electric grinder/mortar and pestle, where water will be added to it until it forms a paste with the consistency of pancake batter.
[404] Liquid mixture can then be brushed onto products to be glazed.

RECOVERY PROCESS VIA REDUCTION AND PIPCO[405, 406]

Recovery (Chemical)



Process Description



Advantages

- Good conversion yields (>96%) can be achieved after a reaction time of 20 minutes.
- Sulphur with a purity of 95-99% can be produced.
- This recovery process based on laboratory and pilot studies seems to be economically feasible for gypsum.

Limitations

- The usage of gypsum pellets is expected to have better conversion of gypsum to CaS compared to powdered mixture.

Recommendations/ Further Research Required

- Optimal conditions (CO_2 flow rate, temperature, pressure and hydrodynamics) are required to obtain high purity elemental sulphur.

WAC

- Waste gypsum preferably in pellet form

Current Application

- Pilot study has been conducted overseas, e.g., in South Africa.

TRL 7

System prototype demonstration in operational environment

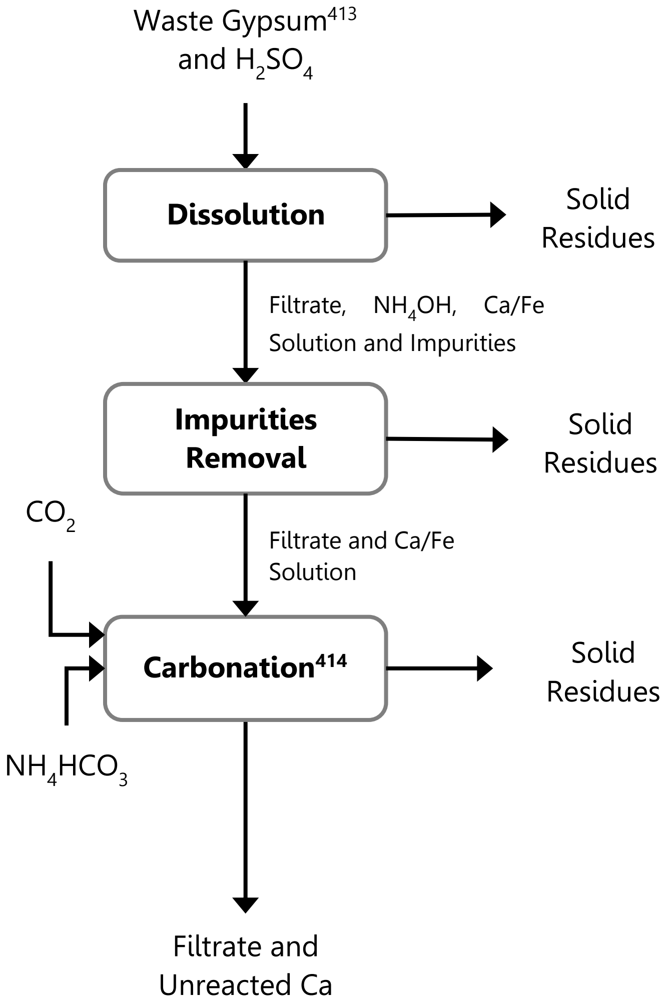
---

[405] N R Mbhele *et al.*, *Recovery of Sulphur from Waste Gypsum*, 2009.
[406] N R Nengovhela *et al.*, *Recovery of sulphur and calcium carbonate from waste gypsum*, 2007.
[407] Waste gypsum will be reduced to calcium sulphide using reducing agents, like coal or activated carbon, carbon disulphide, or carbon monoxide and hydrogen, via thermal decomposition at elevated temperature of 1100˚C.
[408] Calcium sulphide obtained will then be suspended in water to form a CaS slurry. From the slurry, the H_2S is stripped off with CO_2 fed into the reactor.
[409] CaS slurry will then convert to elemental sulphur via the PIPco process (using potassium citrate buffer solution to absorb SO_2).

REUSED FOR INDIRECT CARBONATION[410, 411, 412]

Recovery (Chemical)

Process Description



WAC

- RG and PG

Current Application

- Pilot plant for bauxite residue has been constructed and in operation in China.

Advantages

- Main composition of waste gypsum is sulphate, which has high carbonation reactivity even at room temperature and atmospheric pressure.
- Calcium conversion efficiency can reach almost 100% at moderate conditions.

Limitations

- Excess alkaline solution should be added during carbonation process, which can be uneconomic due to higher value of alkalis.

Recommendations/ Further Research Required

- Process parameter optimization and equipment design for scale-up applications should be extensively investigated (particularly on the efficiency and sufficiency of mass or heat transfer).
- Investigation should also be done on the behaviour and distribution of heavy metals during the carbonation process.
- Life cycle assessment (LCA) technique should be introduced and evaluated for mineral carbonation and its optimization.

TRL 7

System prototype demonstration in operational environment

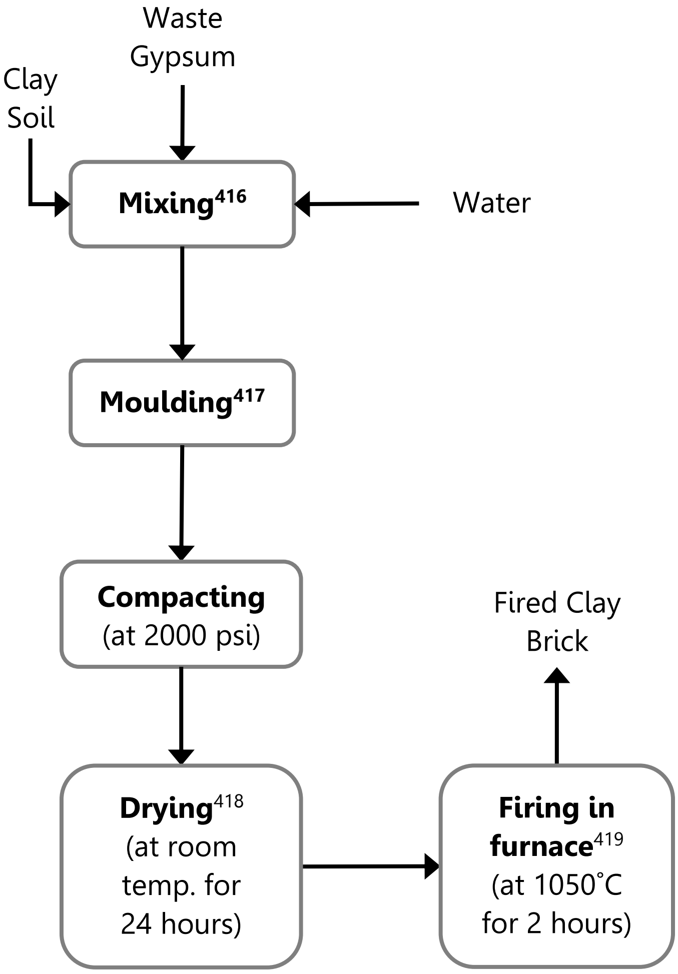
---

410 A Azdarpour *et al., CO2 sequestration using red gypsum via pH-swing process*, 2017.
411 M G Lee *et al., Mineral carbonation of flue gas desulphurisation gypsum for CO2 sequestration*, 2012.
412 W Liu *et al., CO2 mineral carbonation using industrial solid wastes: A review of recent developments*, 2021.
413 This method is suited for red gypsum (RG), and phosphogypsum (PG).
414 The impurities (mainly iron) will then be removed from the solutions by adding NH_4OH. CO_3^{2-} will be added in two different ways (using pure CO_2 and NH_4HCO_3 addition) to the calcium-rich solutions to precipitate $CaCO_3$.

FIRED CLAY BRICK PRODUCTION[415]

Recovery (Physical)

Process Description



WAC

- High CaO, MgO and Na_2O content

Current Application

- Practiced by local industry players.

Advantages

- Gypsum has the potential to bind soil particles and enhance the strength of soil mixtures, especially in a dry environment.
- High presence of CaO, MgO and Na_2O in gypsum waste could be fluxing agents that can decrease firing temperature, hence lowering the energy consumption used during firing stage.

Limitations

- The drying process should be carried out subsequently to prevent disintegration.
- Gypsum waste tend to get burnt away during the firing process, creating pores.
- Bricks produced may absorb more water that could potentially lead to volume changes and cause cracking.

Recommendations/ Further Research Required

- Further investigation on emissions released during firing process of manufacturing the gypsum bricks shall be conducted.

T R L 9

Actual system proven in operational condition

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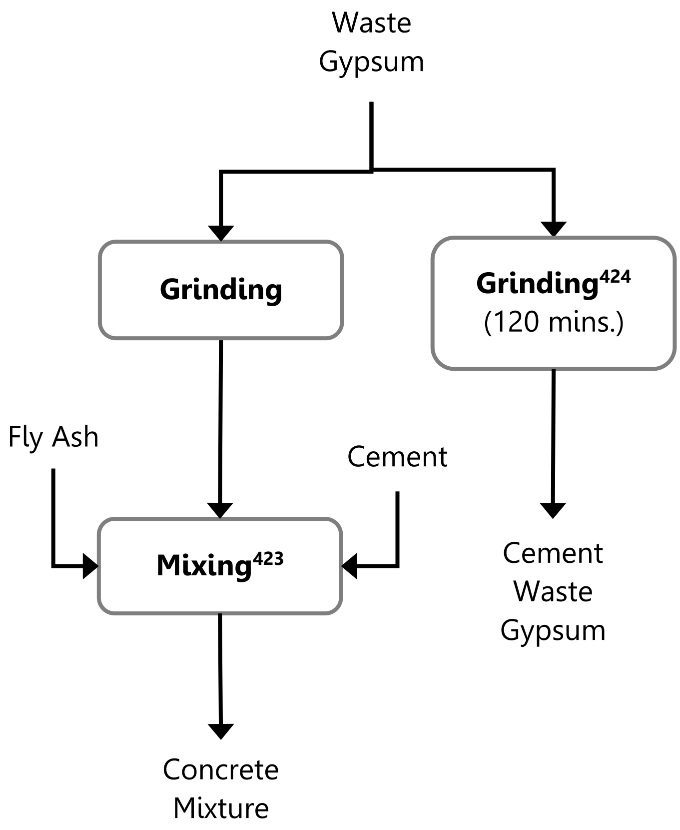
415 See note 376.
416 Clay soil and waste gypsum will be mixed with a predetermined amount of water using a mechanical mixer.
417 After the mixture is homogeneously prepared, the samples will be put into a mould and then compacted at pressure of 2000 psi.
418 Samples will then be dried at room temperature for 24 hours and another 24 hours in the oven at 105˚C.
419 Samples will then be gradually fired in the furnace up to a firing temperature of 1050˚C for two hours.

CONCRETE AND CEMENT APPLICATIONS[420, 421, 422]

Recovery (Physical)

Process Description



WAC

- Low moisture content
- Compressive strength

Current Application

- Practiced by local industry players.
- Practiced by overseas industry players, e.g., in USA.

Advantages

- Replacing concrete and cement with more sustainable and eco-friendly supplementary material is an effective method to reduce the environmental footprint.

Limitations

- As the contents of waste gypsum varies across industries, a series of tests (e.g., physical behaviour of the matrix formed, calorimetric analysis, mechanical resistances, leaching and volumetric tests) to understand the physical properties of the cement mixtures will need to be conducted prior to application.

Recommendations/ Further Research Required

Concrete application

- Complete mechanism and impacts in mixing waste gypsum should be fully understood prior to commercial application.

Cement application

- Different types of waste gypsum contains different amounts of dihydrate, hemihydrate and anhydrate which may require further studies and proper content control during mixing.

TRL 9

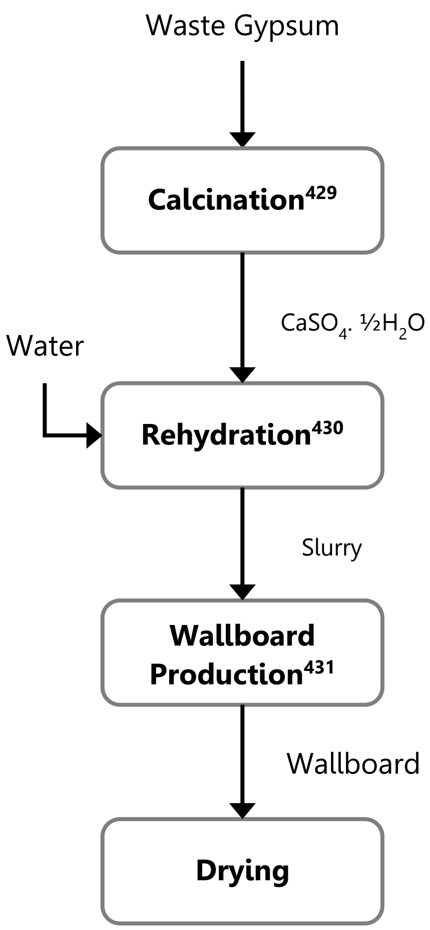
Actual system proven in operational condition

[420] C Chandara *et al., Use of waste gypsum to replace natural gypsum as set retarders in Portland cement*, 2009.
[421] M J Gazquez *et al., Evaluation of the use of TiO_2 industry red gypsum waste in cement production*, 2013.
[422] S Hansen and P Sadeghian, *Recycled gypsum powder from waste drywalls combined with fly ash for partial cement replacement in concrete*, 2020.
[423] Concrete mixes will be prepared by combining ground waste gypsum with fly ash as supplementary cementing materials.
[424] Clinker and 3-5wt% of waste gypsum will be ground for 120 minutes in a ball mill to produce cement waste gypsum. Amount of waste gypsum used in clinker is dependent on its purity. Waste gypsum retards the setting times of the cement.

WALLBOARD PRODUCTS MANUFACTURING[425, 426, 427, 428]

Recovery (Thermal)

Process Description



Advantages

- Reusing waste gypsum helps to save up landfill space and reduce the need to extract raw materials.

Limitations

- Material must be evaluated more closely due to the possible presence of trace contaminants.

Recommendations/ Further Research Required

- Proper control of content of hemihydrate in waste gypsum is required before use as a replacement for natural gypsum.

WAC

- <10 % moisture content
- 2-3 % by weight impurities

Current Application

- Practiced by overseas industry players, e.g., in USA.

TRL 9

Actual system proven in operational environment

[425] See note 369.
[426] Gyproc, *Gypsum Board – Uses and Benefits*, undated.
[427] A Jiménez-Rivero and J García-Navarro, *Management of end-of-life gypsum in a circular economy*, 2020.
[428] T G Townsend and K Cochran, *Recycling Gypsum Drywall Recovered from Deconstruction Projects*, 2015.
[429] Waste gypsum is first calcined, a process that heats the mineral to remove part of the water, resulting in $CaSO_4 \cdot ½ H_2O$.
[430] The stucco that is formed is then rehydrated by mixing with water, and the slurry created can be spread onto a moving continuous sheet of paper and sandwiched between another layer of paper.
[431] This continuous sheet of wallboard is allowed to harden for several minutes, cut into panels and then sent to a kiln for final drying.

4.2.8 SW 321 – Rubber or Latex Wastes

SW 321 comprises of rubber and latex wastes containing organic solvents or heavy metals, which may be generated from waste rubber products and by-product latex wastes or rubber sludge from rubber product manufacturing processes. The focus of this Chapter will be mainly discussed on the latex wastes from rubber product manufacturing processes.

For further understanding on the chemical properties of latex wastes, chemical characterization of raw latex waste is summarized from average values taken from a few different glove manufacturing plants (**Table 4-21**):

Table 4-21: Results of Chemical Characterization of Latex Waste from Dipping Tank[432]

Parameters	Coagulated Lump from Factories			Average
	A	B	C	
Moisture (%)	22.2	32.61	14.67	23.16
Polymer content (%)	62.5	57.82	61.09	60.47
Ash (%)	0.3	0.67	8.73	3.23
Calcium carbonate, $CaCO_3$ (%)	12.5	6.6	10.75	9.95
Zinc oxide, ZnO (%)	0.16	0.43	1.48	0.69
Accelerators and antioxidant (%)	0.2	0.61	0.35	0.39
Total sulphur (%)	1.09	0.81	2.05	1.32
Others[433]	1.06	0.45	0.9	0.80

4.2.8.1 Reuse Applications

There are no reuse applications for SW 321 under the reuse category as defined in **Chapter 3.3, Table 3-1**.

4.2.8.2 Recovery Technologies

Recovery technologies for rubber or latex wastes consists of all four (4) methods, i.e., physical, chemical, biological and thermal, management technologies. There are some similarities in the recovery processes, where it mainly involves in the devulcanization of rubber by selectively breaking the sulphur-sulphur (S-S) and carbon-sulphur (C-S) chemical bonds without breaking the backbone network and without degrading the material.[434] The devulcanized rubber can be mixed with virgin rubber or other kinds of matrices to give new compounds without generating a significant decrease in mechanical and physical properties.[435].

A summary of recovery technologies for SW 321 can be referred in **Table 4-22**.

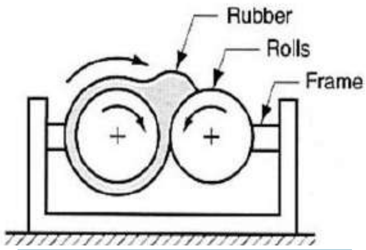
[432] V Devaraj *et al., Utilisation of Waste from Natural Rubber Glove Manufacturing Line*, 2023.
[433] Traces of heavy metal (Ti, Cd, Pb), silicates and degraded rubber found in acetone extract which were not analysed.
[434] L Asaro *et al., Recycling of rubber wastes by devulcanization*, 2018.
[435] ibid.

Table 4-22: Summary of Recovery Technologies for SW 321 (Latex Waste)

Recovery Technologies	Method	Technology Readiness Level (TRL)	Reference Page
De-link process	Chemical	4 *Technology validated in lab*	4-113
Gasification	Thermal	4 *Technology validated in lab*	4-114
Renewable Resource Material (RRM) reclaiming process	Chemical	4 *Technology validated in lab*	4-115
Biodegradation of *cis*-1,4-polyisoprene chain	Biological	4 *Technology validated in lab*	4-116
Pyrolysis	Thermal	8 *System complete and qualified*	4-117
TAK system	Physical	9 *Actual system proven in operational environment*	4-118
Arizona refinery system (wet process)	Physical	9 *Actual system proven in operational environment*	4-119
Rubber reclamation via mechanical recycling	Physical	9 *Actual system proven in operational environment*	4-120
Rubber reclamation via microwave method	Physical	9 *Actual system proven in operational environment*	4-121
Rubber reclamation via ultrasonic method	Physical	9 *Actual system proven in operational environment*	4-122
Rubber reclamation via wet or solution grinding	Physical	9 *Actual system proven in operational environment*	4-123
Rubber reclamation via cryomechanical process	Physical	9 *Actual system proven in operational environment*	4-124
Rubber reclamation via oxidation	Chemical	9 *Actual system proven in operational environment*	4-125
Rubber reclamation via organic disulphides and mercaptans	Chemical	9 *Actual system proven in operational environment*	4-126

DE-LINK PROCESS[436, 437]

Recovery (Chemical)



Process Description

Fine Latex Waste

↓

De-Vulc Reactant → **Milling[438]**

↓

Devulcanized Rubber

Advantages

- Reclaimed rubber product blend from this process have high Mooney viscosity, tanδ and 300% modulus.

Limitations

- Tensile strength, elongation at break and tear resistance for these products are low but are very similar to those for the virgin materials.

Recommendations/ Further Research Required

- More studies are required to improve tensile strength, elongation at break and tear resistance of products blended with devulcanized rubber.

WAC

- <40 mesh rubber crumb

Current Application

- Laboratory-scale study

T R L 4

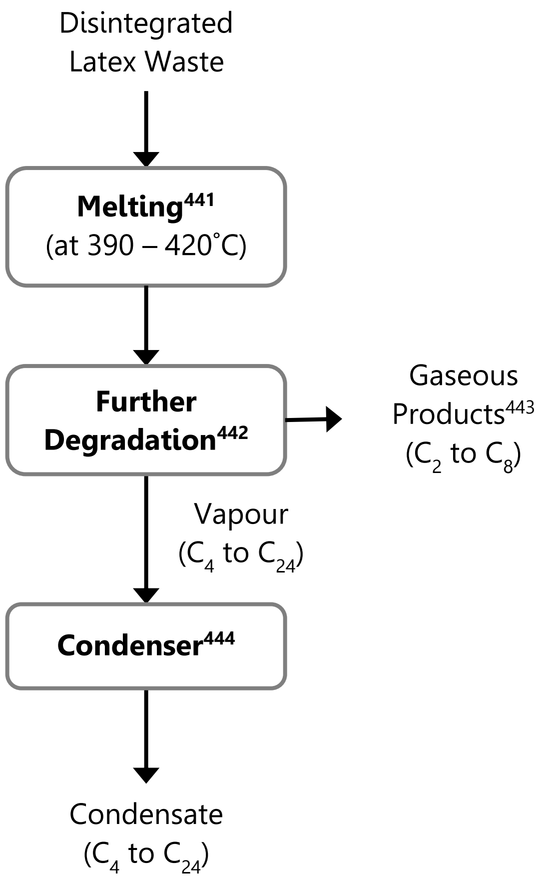
Technology validated in lab

[436] B Adhikari, D De and S Maiti, *Reclamation and recycling of waste rubber*, 2000.
[437] J Sapkota, *Influence of Clay Modification on Curing Kinetics of Natural Rubber Nanocomposites*, 2011.
[438] In this process, 100 parts of 40 mesh or finer crumb will be mixed with 2-6 parts of De-Vulc reactant in an open two roll mixing mill to form devulcanized rubber.

GASIFICATION[439, 440]

Recovery (Thermal)

Process Description



WAC

- Disintegrated latex waste

Current Application

- Local industry players are currently undergoing feasibility studies.
- Laboratory-scale study conducted by overseas players.

Advantages

- Gasification process is fast.
- The problems with the heat transfer resistance between the particles of wastes and the heating medium is overcome due to direct contact between rubber and molten metal.
- Ratio of the amount of gaseous product to amount of liquid product is less than resulted in other thermal decomposition processes.
- Hold-up time of wastes in the reactor and reaction time are shorter than classical reactors applied for rubber pyrolysis.

Limitations

- Thermal cracking processes of rubber in the reactor with molten metal bed (as other thermal processes) will only be cost-effective if all of the obtained products, including carbon black etc., may be recycled and used for producing fuel and other useful semi-products.

Recommendations/ Further Research Required

- Further research is required for full recovery of all obtained products for better cost-effectiveness.

T R L 4

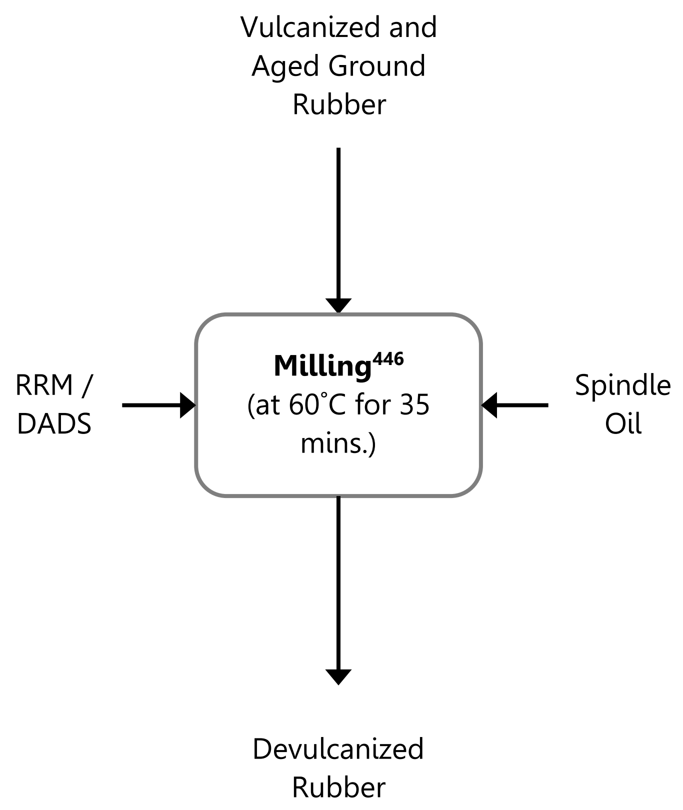
Technology validated in lab

[439] M Stelmachowski and K Słowiński, *Conversion of waste rubber as an alternative route to renewable fuel production*, 2009.
[440] Top Glove, 2023.
[441] Disintegrated rubber particles will be melted and decomposed in a tubular reactor from 390 to 420˚C. Products of the degradation and un-decomposed components will flow out to the external tube for further degradation.
[442] Further degradation will then be carried out in the molten metal bed in the external tube and on the surface to give final products, i.e., mixture of hydrocarbons.
[443] Gaseous product (below 15 wt%), the mixture of un-condensable hydrocarbons (C_2 to C_8), will flow out from the reactor and be collected.
[444] Vapours that flow out from the reactor (C_4 to C_{24}) will be condensed in coolers and collected (over 40 wt%). Over 80 mol% of liquid hydrocarbons mixture was the fraction C_4-C_{10}, which may be used in petrochemical, refinery or recycled for rubber product manufacturing.

RENEWABLE RESOURCE MATERIAL (RRM) RECLAIMING PROCESS[445]

Recovery (Chemical)

Process Description



WAC

- Vulcanized and aged ground rubber

Current Application

- Laboratory-scale study

Advantages

- The DADS breaks into radicals as the temperature rises due to mechanical shearing, such radicals combine with the broken polymer chain radical and thereby prevent the recombination of these polymer radicals which explains the increase of sol fraction with increase in milling time.

Limitations

- Lower molecular weight of the sol fraction obtained at lower milling time than that obtained at higher milling time due to the action of RRM or DADS on the sol fraction.

Recommendations/ Further Research Required

- Studies on economic viability of the technology is required for chemical usage.

TRL 4

Technology validated in lab

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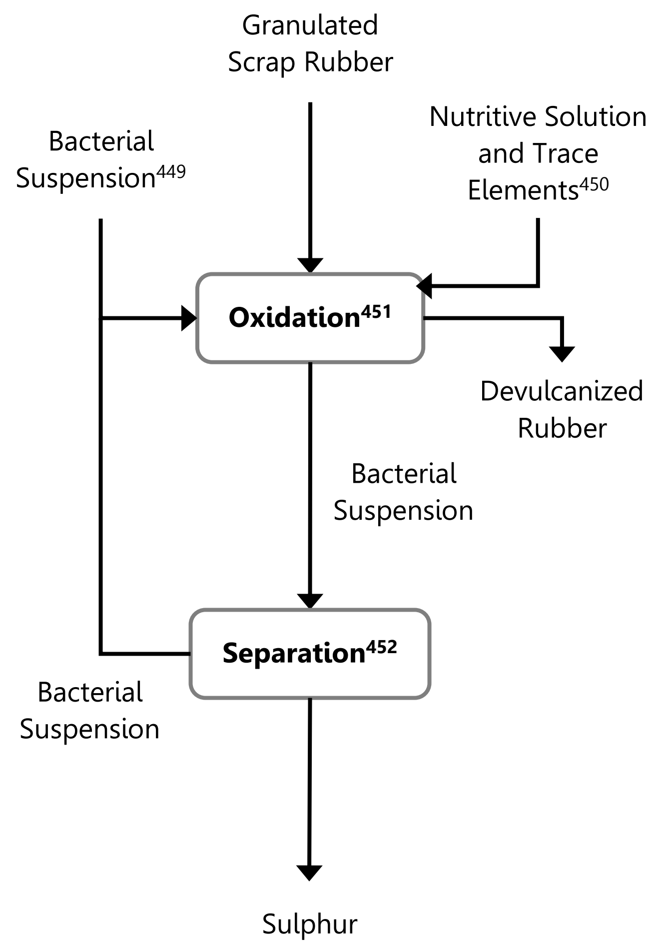
[445] See note 436.

[446] Vulcanized and aged ground rubber will be milled in a two roll mixing mill for 35 minutes at 60˚C with simultaneous addition of the RRM and spindle oil or diallyl disulphide (DADS) and spindle oil separately.

BIODEGRADATION OF *CIS*-1,4-POLYISOPRENE CHAIN[447, 448]

Recovery (Biological)

Process Description



WAC

- Granulated scrap rubber of 5-7 mm

Current Application

- Laboratory-scale study with method patented.

Advantages

- Various modifications and structural changes may be made without departing in any way from the spirit of the invention.
- Process works at a lower cost, faster and with improved output, as compared to conventional methods.

Limitations

- Different bacteria require different optimum pH levels for oxidation to occur.

Recommendations/ Further Research Required

- Studies are recommended to be conducted on the splitting off sulphur to the superficial layer of the scrap rubber particles and if the core of the particles remain in the state of scrap rubber.

T R L 4

Technology validated in lab

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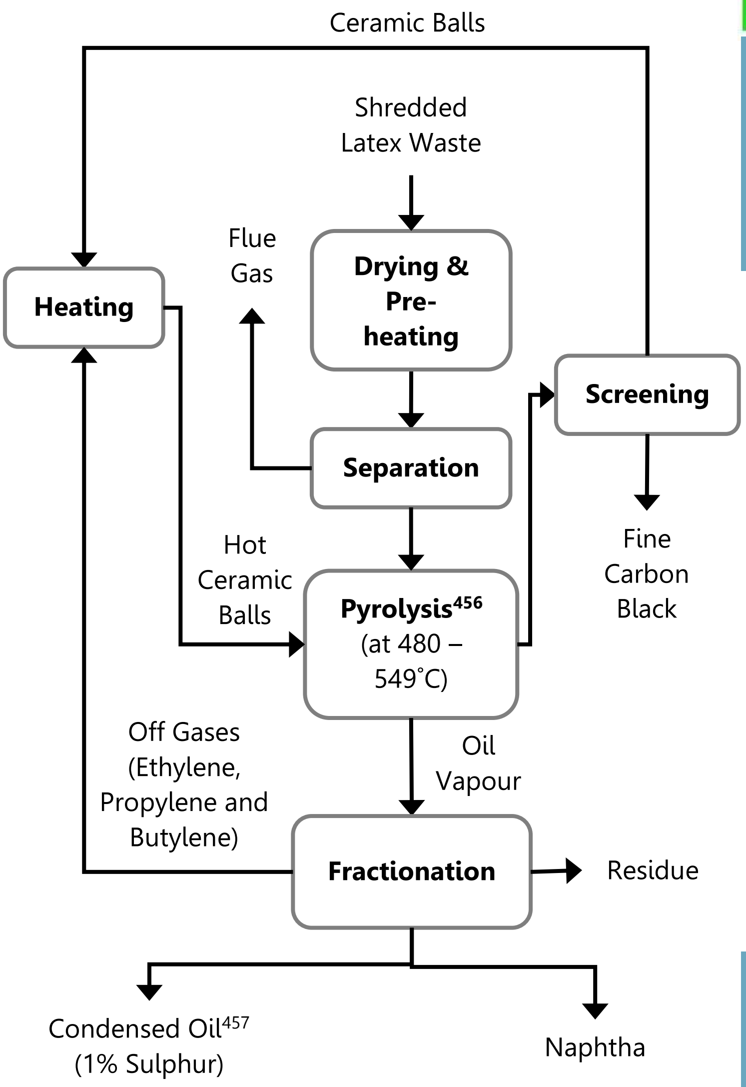
447 See note 436.
448 Straube *et al.*, *Patent No. US5275948A*, 1994.
449 Bacterium belonging to the genus *Narcadia* will be used to lead to biodegrade natural rubber vulcanates.
450 Nutritive solution and trace elements will be added through a supply line to the bacterial suspension continuously or at specific time intervals.
451 Best results can be obtained with *T.thioparus* with a particle size of 100 - 200µm, where 4.7% of the total sulphur of the rubber powder can be oxidized to sulphate within 40 days.
452 After the sulphur has been separated, the suspension devoid of sulphur is again supplied into the container.

PYROLYSIS[453, 454, 455]

Recovery (Thermal)

Process Description



WAC

- Shredded/chopped latex wastes

Current Application

- Attempted by industry players overseas, e.g., Kobe Steel in Japan, Tosco in US, Tyrolysis in UK, Ebenhausen in Germany, but none survived.

Advantages

- Able to generate gas and oil that can be used as a fuel and possibly for other applications.

Limitations

- Hydrocarbon monomers or even oligomers cannot be expected to be recovered from the complex rubber structures by pyrolysis.
- If the formulation contains 30% of carbon black or white filler plus other inorganic materials, reduced yields are expected.
- There can be size reduction necessity for rubber articles in order to facilitate heat transfer, i.e., by fluid bed energy.

Recommendations/ Further Research Required

- Carbon must be carefully chosen to achieve specific properties in compounded rubbers.

TRL 8

System complete and qualified

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453 See note 436.
454 See note 437.
455 O Masek, W Buss and A Roy-Poirier, *Consistency of biochar properties over time and production scales*, 2018.
456 The rubber will pyrolyze and form a solid residue, oil vapour and off gases; the condensed oil separates in a fractionator and the gas is used to heat the ceramic balls.
457 The condensed oil can be substituted directly for fuel oil.

TAK SYSTEM[458, 459, 460]

Recovery (Physical)

Process Description

Fine and Coarse Waste Rubber Particles

Dense Graded Aggregate Mixture

Mixing[461, 462]

Rubber Modified Asphalt Concrete Paving Mixture

WAC

- Ground rubber particles from whole passenger and semi and truck tires of < 16 mesh size
- Cured rubber

Current Application

- Practiced by industry players overseas.

Advantages

- Binder produced from this method provides superior elastic properties.
- The TAK System can be designed with conventional testing equipment and conventional design criteria.

Limitations

- A pre-reaction or pre-treatment of crumb rubber with a catalyst may be needed to achieve the optimum crumb rubber particle swelling.

Recommendations/ Further Research Required

- Further research is required before implementation.

TRL 9

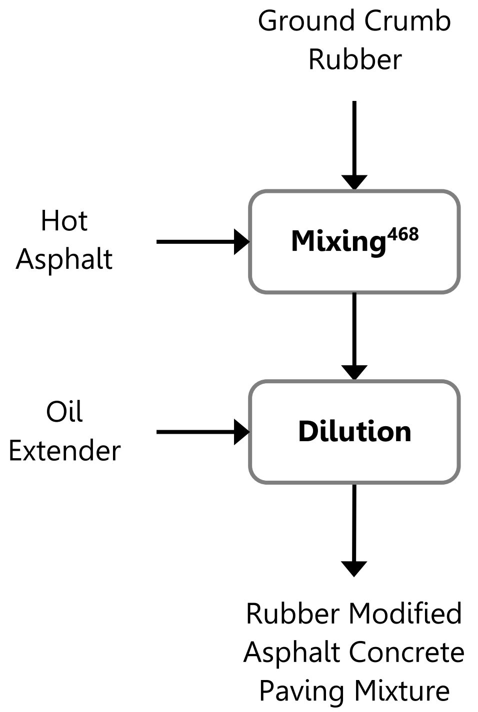
Actual system proven in operational environment

458 See note 436.
459 Los Angeles County Public Works, *Rubberized Asphalt*, 2023.
460 H B Takallou and A Sainton, *Advances in Technology of Asphalt Paving Materials Containing Used Tire Rubber*, 1992.
461 Rubber modified asphalt concrete paving mixture can be prepared by adding 3 wt% of fine and course rubber particles to a dense graded aggregate mixture.
462 In this system, the rubber content in the composition should not exceed 2% for open-graded or dense-graded wearing course, and 3% for binder course, by total weight of the mixture.

ARIZONA REFINERY SYSTEM (WET PROCESS)[463, 464, 465, 466, 467]

Recovery (Physical)

Process Description



WAC

- Ground crumb rubber
- > 40% polymer
- < 10% ash content
- < 2% zinc content
- < 2% sulfur content
- < 2% accelerators and antioxidants
- < 10% calcium carbonate

Current Application

- Practiced by industry players overseas, e.g., in USA.

Advantages

- Reaction of rubber with asphalt binder displayed improved properties in viscosity, ball and ring softening point, elasticity and resilience at low temperatures and cohesiveness.
- Elastic quality of the asphalt mixture is required to be maintained by undissolved rubber particles that serve as units of elastic interference to the propagation of cracking.

Limitations

- Rubberized binder must be used within hours of its production, so the high cost of mobilizing the specialized equipment (blending unit, metering unit, storage tanks, etc.) at the production facility must be recovered in the cost per ton of rubberized binder used on that project.

Recommendations / Further Research Required

- Further research is needed to examine the permeability and moisture damage characteristics of rubberized asphalt pavements in various exposure conditions.
- Further field testing is required on rubberized asphalt pavements constructed in different zones to gain understanding of the behavior of rubberized asphalt in aggressive exposure conditions.

TRL 9

Actual system proven in operational environment

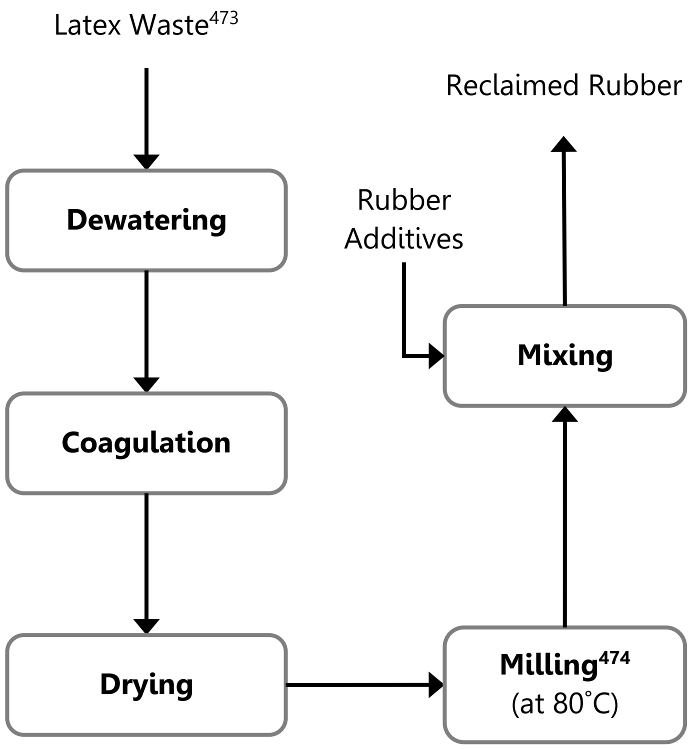
---

[463] See note 432.
[464] See note 436.
[465] See note 460.
[466] S A Alfayez, A R Suleiman and M L Nehdi, *Recycling Tire Rubber in Asphalt Pavements: State of the Art*, 2020.
[467] M B Takallou and H B Takallou, *Benefits of Recycling Waste Tires in Rubber Asphalt Paving*, 1991.
[468] 18% to 22% of ground crumb rubber by weight of binder can be mixed with hot asphalt cement and diluted with an oil extender for ease of application.

RUBBER RECLAMATION VIA MECHANICAL RECYCLING[469, 470, 471, 472]

Recovery (Physical)

Process Description



Advantages

- A particle size of 200 µm can be achieved.
- High surface area.

Limitations

- Temperature can reach up to 130˚C, which might require excess water for cooling as crumb rubber will undergo oxidation due to heat.

WAC

- Vulcanized rubber waste
- > 40% polymer
- < 10% ash content
- < 2% zinc content
- < 2% sulphur content
- < 2% accelerators and antioxidants
- < 10% calcium carbonate

Recommendations/ Further Research Required

- Further research is required before implementation.

Current Application

- Practiced by local industry players.
- Practiced by overseas industry players.

T R L 9

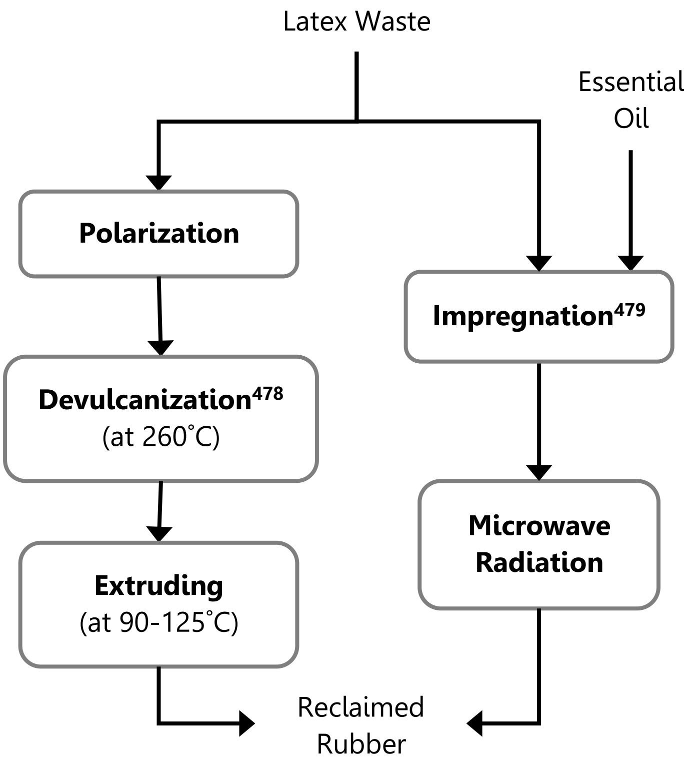
Actual system proven in operational environment

[469] See note 436.
[470] See note 440.
[471] H Chittella *et al.*, *Rubber waste management: A review on methods, mechanism, and prospects*, 2021.
[472] Indiamart, *Black Course Reclaim Rubber*, 2023.
[473] Latex waste is dewatered/compressed, coagulated, and then dried.
[474] Dried latex sheets pass through mill roll at 80˚C. It will then be mixed with rubber additives to form reclaimed rubber.

RUBBER RECLAMATION VIA MICROWAVE METHOD[475, 476, 477]

Recovery (Physical)

Process Description



WAC

- Polarized rubber waste
- > 40% polymer
- < 10% ash content
- < 2% zinc content
- < 2% sulphur content
- < 2% accelerators and antioxidants
- < 10% calcium carbonate

Current Application

- Practiced by overseas industry players.

Advantages

- Economical, ecologically sound method of reusing elastomeric waste to the same process, and it produces similar product with equivalent physical properties.
- Cost of devulcanized hose and inner tube material by microwave method is only a fraction of the cost of the original compound.
- Transformation from waste to refined stock ready for remixing takes place in only five minutes with usually 90 – 95% recovery of rubber.

Limitations

- Microwave energy is insufficient to sever polymer chain degradation.

Recommendations/ Further Research Required

- Further research is required before implementation.

T R L 9

Actual system proven in operational environment

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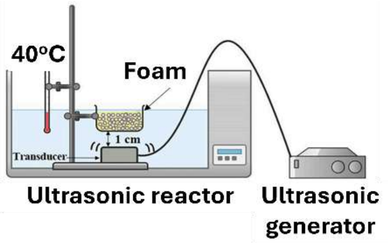
[475] See note 436.
[476] See note 471.
[477] Kerone Engineering Solutions Ltd., *Microwave Heating for Rubber Industry*, 2023.
[478] Polarized latex waste can be devulcanized via microwave energy at a temperature in excess of 260˚C to yield a mass, which will then be fed through an extruder, which extrudes the rubber at a temperature of 90 – 125˚C.
[479] Another process involves the impregnation of waste rubber with an essential oil and then heat-treating the impregnated material under reduced pressure with microwave radiation to form reclaimed rubber.

RUBBER RECLAMATION VIA ULTRASONIC METHOD[480, 481, 482]

Recovery (Physical)



Process Description

Latex Waste

↓

Ultrasonic Disintegration[483, 484]
(~20 kHz at power intensity > 100W)

↓

Reclaimed Rubber

WAC

- Solid rubber articles
- > 40% polymer
- < 10% ash content
- < 2% zinc content
- < 2% sulphur content
- < 2% accelerators and antioxidants
- < 10% calcium carbonate

Current Application

- Practiced by overseas industry players.

Advantages

- Causes significant degradation of polymer chains.

Limitations

- Molecular weight of sol fraction decreases as during ultrasound treatment C-C bonds may also break, which requires revulcanization.

Recommendations/ Further Research Required

- Further research is required before implementation.

T R L 9

Actual system proven in operational environment

480 See note 436.
481 See note 471.
482 B Sukkaneewat and S Utara, *Ultrasonic-assisted Dunlop method for natural rubber latex foam production*, 2022.
483 Solid latex wastes can be immersed into a liquid, and then put with a source of ultrasonic energy whereby the bulk rubber effectively disintegrated upon contact and dissolved into liquid.
484 In this process, ultrasonic irradiation is in the range of about 20 kHz and at a power intensity of greater than 100 W.

RUBBER RECLAMATION VIA WET OR SOLUTION GRINDING[485, 486, 487]

Recovery (Physical)

Process Description

Latex Waste

↓

Grinding[488]

↓

Reclaimed Rubber[489]

Advantages

- Allows good processing, producing relatively smooth extrudates and calendered sheets.

Limitations

- High energy consumption.
- Extra drying makes process costlier.

WAC

- Course ground rubber crumbs (10-20 mesh)
- > 40% polymer
- < 10% ash content
- < 2% zinc content
- < 2% sulphur content
- < 2% accelerators and antioxidants
- < 10% calcium carbonate

Recommendations/ Further Research Required

- Further research is required before implementation.

Current Application

- Practiced by local industry players.
- Practiced by overseas industry players.

T R L 9

Actual system proven in operational environment

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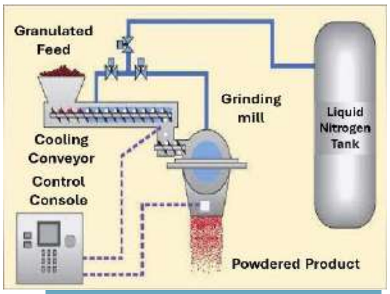
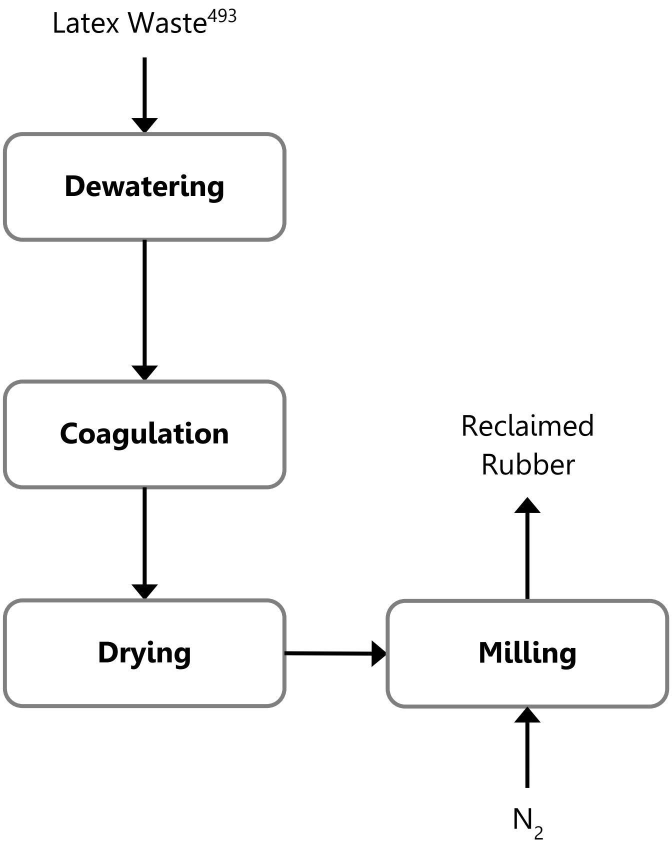
485 See note 436.
486 See note 471.
487 Indiamart, *Rubber Grinding Mill Machine*, 2023.
488 This is a modified ambient grinding process. The process involves putting a course ground waste rubber crumbs (10 – 20 mesh) into a liquid medium, usually water, and grinding between two closely spaced grinding wheels.
489 Particle sizes of 400 – 500 mesh can be produced.

RUBBER RECLAMATION VIA CRYOMECHANICAL PROCESS[490, 491, 492]

Recovery (Physical)



Process Description



Advantages

- Particle size of 40-60 mesh can be achieved.
- Equipment and operating costs are lower.
- Increased productivity.
- Product has better flow characteristics than ambient ground rubber.

Limitations

- High cost of liquid nitrogen.
- Smoother surface area resulting in poor binding ability.

WAC

- Small-sized vulcanized rubber
- > 40% polymer
- < 10% ash content
- < 2% zinc content
- < 2% sulphur content
- < 2% accelerators and antioxidants
- < 10% calcium carbonate

Recommendations/ Further Research Required

- Further research is required before implementation.

Current Application

- Practiced by overseas industry players.

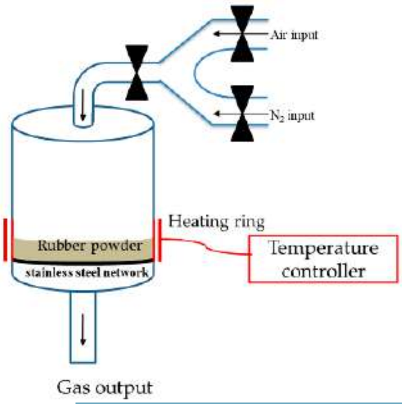
TRL 9

Actual system proven in operational environment

490 See note 151.
491 See note 436.
492 See note 471.
493 Small pieces of latex waste will be placed into liquid nitrogen which will then be transferred to a ball mill and ground in the presence of liquid nitrogen to form fine powder.

RUBBER RECLAMATION VIA OXIDATION[494, 495, 496]

Recovery (Chemical)



Process Description

Latex Waste

↓

Shredding[497]

↓

Heating[498] (at ~370˚C for

← Isocyanide, Chloride and Carbon

↓

Oil, Rubber Polymer Materials, Carbon

Advantages

- Free of hazardous emissions.

Limitations

- Requires addition of soybean oil in bath mixture to provide a safer and more economical process.

WAC

- Shredded rubber waste
- > 40% polymer
- < 10% ash content
- < 2% zinc content
- < 2% sulphur content
- < 2% accelerators and antioxidants
- < 10% calcium carbonate

Recommendations/ Further Research Required

- Further research is required before implementation.

Current Application

- Practiced by overseas industry players.

TRL 9

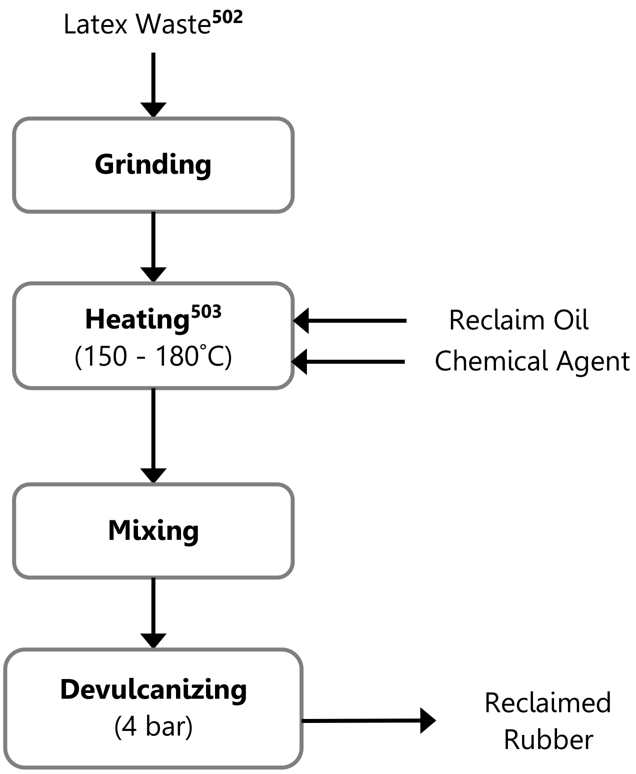
Actual system proven in operational environment

[494] See note 463.
[495] See note 471.
[496] L H Chou *et al., Effects of partial oxidation of crumb rubber on properties of rubberized mortar*, 2010.
[497] Shredded latex waste will be added into a batch of isocyanide, polyurethane, latex and soybean oil.
[498] The resultant mixture will be heated at approximately 370˚C for 10 minutes to obtain the recovered products, i.e., oil, rubber polymer materials and carbon.

RUBBER RECLAMATION VIA ORGANIC DISULPHIDES AND MERCAPTANS[499, 500, 501]

Recovery (Chemical)

Process Description



WAC

- Finely ground rubber scraps
- > 40% polymer
- < 10% ash content
- < 2% zinc content
- < 2% sulphur content
- < 2% accelerators and antioxidants
- < 10% calcium carbonate

Current Application

- Practiced by overseas industry players.

Advantages

- Large numbers of reclaiming agents are available to chemically reclaim latex waste.

Limitations

- Reclaimed rubber via this method possesses very poor mechanical properties.

Recommendations/ Further Research Required

- Further research is required before implementation.

TRL 9

Actual system proven in operational environment

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[499] See note 463.
[500] See note 471.
[501] Alibaba, *Reclaiming Agent/Rubber Activator RA480 & RA790*, 2023.
[502] Large number of chemical reclaiming agents have been developed for natural and synthetic rubbers, e.g., viz. diphenyl disulphide, dibenzyl disulphide, diamyl disulphide, bis(alkoxy aryl) disulphides, butyl mercaptan and thiophenols, xylene thiols and other mercaptans, phenol sulphides and disulphides.
[503] Finely ground scrap is heated in saturated steam at a high temperature (150 – 180˚C) with the addition of reclaim oil and chemical agent, then allowed to mix thoroughly. Scraps are rolled into a pressurized devulcanizer (4 bar).

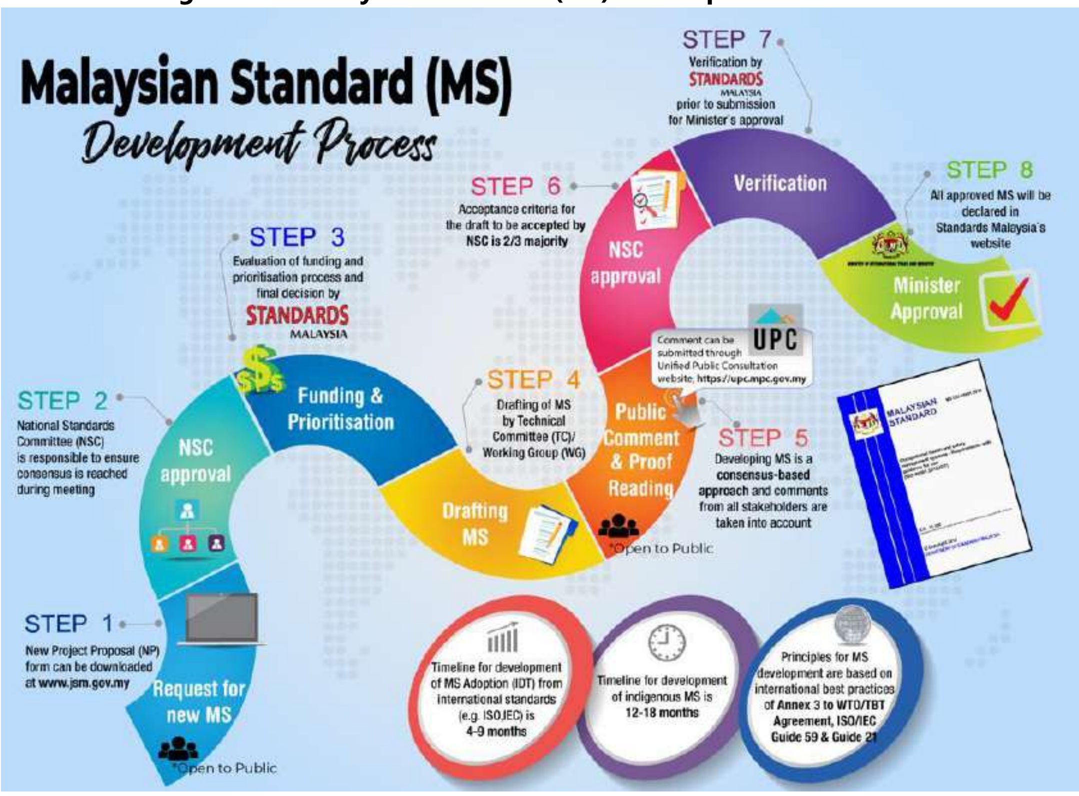
4.3 SPECIFICATIONS OF PRODUCTS RESULTING FROM REUSE AND RECOVERY PROCESSES

Following the completion of the product development from scheduled waste, it is essential to establish product specifications or standards before introducing the product to the market. These specifications outline crucial requirements for the product's design, functionality, or any new features, ensuring its safety, quality, reliability, and consistency. Product standards are vital to guarantee the product's usability and meet user expectations.

Standards are categorized at various levels, determined by geographical, political, or economic factors. These levels include International Standards, Regional Standards, National Standards, Association Standards, and Industrial/Company/In-house Standards.

In Malaysia, the Department of Standards Malaysia (JSM) plays a pivotal role in creating and publishing national standard documents, known as Malaysian Standard (MS). This process involves consensus-building, extensive stakeholder engagement, and incorporating valuable input and feedback, ensuring the development of high-quality standards. The creation of Malaysian Standard is a well-defined process, as depicted in **Figure 4-5**.

Figure 4-5: Malaysian Standard (MS) Development Process[504]



504 Department of Standards Malaysia, *MS Development Process*, 2023.

Based on the characteristics and technology available for the reuse and recovery of the selected key scheduled wastes, there are three (3) main categories of products resulting from reuse and recovery process, which are:

- Construction material
- Agriculture
- Recovered precious metals/materials

These recovered products shall comply to the standards published by JSM or known standards, such as the British Standards (BS) and the ASTM International. Future developments of additional standards in accordance with the Malaysian Standards Development Process, where applicable, are possible as the recovery of certain scheduled wastes for a specific usage becomes more prevalent. Nevertheless, the details of product specifications based on existing standards are elaborated in the following Chapters.

4.3.1 Construction Material

The recovery of scheduled wastes, specifically SW 104, SW 204, SW 205 and SW 321, present valuable opportunities for their conversion into alternative raw materials and supplementary materials within the construction industry. These recovered materials find application in various construction products, notably cements and aggregates, aligning with industry quality and safety standards.

The reference standards for these recovered or reclaimed materials are provided in **Table 4-23**, ensuring adherence to established standards.

Table 4-23: Reference Standards for Construction Materials

SW Code	Main Product	Reference Standards[505, 506, 507, 508, 509, 510]
SW 104 – Silico-manganese slag from ferroalloy industries SW 204 – Paper mill sludge SW 205 – Waste gypsum from chemical industries	Supplementary Cementitious Material (SCM) / Cementitious Material / Portland Cement	• MS EN 197 (Cement: Composition, Specifications and Conformity Criteria for Common Cements) • MS 1387 (Specification for Ground Granulated Blast Furnace Slag for Use with Portland Cement) • MS 522: Part 1 (Portland Cement (Ordinary and Rapid-Hardening): Part 1: Specification)

[505] MS indicates Malaysian Standard.
[506] BS indicates British Standards.
[507] BS EN indicates British Standards incorporating a European Standard.
[508] MS EN indicates Malaysian Standard incorporating a European Standard.
[509] CIS indicates Construction Industry Standard developed by the Construction Industry Development Board (CIDB) Malaysia.
[510] ASTM (American Society for Testing and Materials) is an international standards organization.

SW Code	Main Product	Reference Standards[505, 506, 507, 508, 509, 510]
SW 104 – Silico-manganese slag from ferroalloy industries	Aggregates in Concrete	• MS EN 12620 (Aggregates for Concrete)
SW 204 – Paper mill sludge	Fibreboard	• BS EN 622-1 (Fibreboards – Specifications, General Requirements)
SW 204 – Paper mill sludge	Cement Mortar Blocks	• JKR 20800-0183-14 (Standard Specifications for Building Works 2014) • MS 2506-2 (Mortar for Masonry – Specification – Part 2: Masonry Mortar)
SW 204 – Paper mill sludge	Insulating Material	• MS 1020 (Thermal Insulation Products for Buildings – Factory Made Mineral Wool (MW) Products – Specifications)
SW 204 – Paper mill sludge	Lightweight Aggregates (LWA)	• MS EN 12620 (Aggregates for Concrete) • MS EN 2280 (Aggregates for Mortar)
SW 204 – Paper mill sludge SW 205 – Waste gypsum from chemical industries	Fired Clay Brick	• BS EN 771-1 (Specification for Masonry Units – Clay Masonry Units) • MS 76 (Bricks and Blocks of Fired Brickearth, Clay or Shale)
SW 204 – Paper mill sludge SW 205 – Waste gypsum from chemical industries	Concrete Mixture	• MS EN 206 (Concrete – Specification, Performance, Production and Conformity) • CIS 21: 2018 (Ready-Mixed Concrete: Production, Conformity, Transportation and Delivery Criteria for Producers)
SW 205 – Waste gypsum from chemical industries	Wallboard	• ASTM C1396 (Standard Specification for Gypsum Board)
SW 321	Rubber Modified Asphalt Concrete Paving Mixture	• ASTM D6114/D6114M (Standard Specification for Asphalt-Rubber Binder)

An example of the physical requirements for asphalt-rubber binder as extracted from ASTM D6114-97 (Reapproved 2002) can be found in **Table 4-24**. For detailed information on each of the product specifications, the latest versions of the standards as listed in **Table 4-23** should be referred.

Table 4-24: Example of Physical Requirements for Asphalt-Rubber Binder Based on ASTM D6114-97 (Reapproved 2002)[511]

Binder Designation	Unit		Type I[512]	Type II[513]	Type III[514]
Apparent Viscosity, 175°C	cP	min	1500	1500	1500
		max	5000	5000	5000
Penetration, 25°C 100g, 5s	1/10 mm	min	25	25	50
		max	75	75	100
Penetration, 4°C 200g, 60s	1/10 mm	min	10	15	25
Softening Point	°C	min	57.2	54.4	51.7
Resilience, 25°C	%	min	25	20	10
Flash Point	°C	min	232.2	232.2	232.2
Penetration Retention, 4°C	% of original	min	75	75	75

4.3.2 Agriculture

Products derived from scheduled waste recovery for the agricultural sector primarily focus on enhancing soil quality. These products encompass fertilizers and soil conditioners, with their standards governed by the Malaysian Standard, **MS 1517 Organic Fertilizers – Specification** (**Table 4-25** and **Table 4-26**).

Table 4-25: Maximum Permissible Limit of Pathogenic Microbes Based on MS 1517:2012[515]

Pathogen	Unit	Maximum Limit
E. coli	cfu/g	<10
Pseudomonas aeruginosa	cfu/g	<10
Staphylococcus aureus	cfu/g	<10
Salmonella	cfu/g	Absent

Table 4-26: Maximum Permissible Limits of Pollutants Based on MS 1517:2012515F[516]

Pollutant	Unit	Maximum Limit
Arsenic	mg/kg	50
Cadmium	mg/kg	5
Chromium	mg/kg	200
Lead	mg/kg	300
Mercury	mg/kg	2
Nickel	mg/kg	150

[511] ASTM D6114-97 (Reapproved 2002), *Standard Specification for Asphalt-Rubber Binder.*

[512] Type I binders typically include stiffer base asphalt cements and are generally recommended for use in hot climate areas.

[513] Type II binders typically include softer grades of asphalt cement than Type I binders and are generally recommended for use in moderate climate areas.

[514] Type III binders typically include the softest grades of asphalt cements available, and may require softening additives to achieve the specified physical properties and are generally recommended for use in cold climate areas.

[515] MS 1517:2012, *Organic Fertilisers – Specification.*

[516] ibid.

4.3.3 Recovered Precious Metals / Materials

Valuable metals and materials are recoverable from scheduled wastes, frequently re-entering manufacturing processes or industries as alternative raw materials. **Table 4-27** highlighted some of the standards and specifications that can be referred for some of the products obtained through recovery of the selected scheduled wastes. These standards are essential for ensuring the quality, safety, and reliability of the recovered materials, fostering consistency in product performance and environmental sustainability.

Table 4-27: Examples of Recovered Material, Potential New Products and Their Respective Standards/Specifications

SW Code	Examples of Recovered Material	Potential New Products	Standard/ Specifications
SW 103 – Lithium- ion batteries	Lithium chemical	Lithium-ion batteries	IEC 62133-2:2017 (Secondary cells and batteries containing alkaline or other non-acid electrolytes – Safety requirements for portable sealed secondary cells, and for batteries made from them, for use in portable applications – Part 2: Lithium systems)
SW 104 – Silico-manganese slag from ferroalloy industries	Manganese	Ferroalloy	α-manganese with purity of 99.99%[517]
SW 110 – Spent insulated copper wires and cables	Plastic	Wire insulator	• MS 138 (Specification for PVC insulation and sheath of electric cables) • BS 7655 (Specification for Insulation and Sheath Materials for Cables) • BS 6746 (Specification for PVC Insulation and Sheath of Electric Cables)
SW 202 – Spent catalysts	Platinum Group Metals (PGMs)	Catalyst	99.99% purity of PGMs (London Platinum & Palladium Market)
SW 204 – Paper mill sludge	Fibre	Animal Feed	• MS 565 (Specification for Mineral Mixtures or Supplementing Poultry Feeds) • MS 20 (Poultry Feeds – Specification)

[517] See note 115.

SW Code	Examples of Recovered Material	Potential New Products	Standard/ Specifications
		Moulded Pulp Products	• Thickness: TAPPI T411 om-97 • Tensile: ISO 1994-2 • Axial Compression: TAPPI T 826 • Flexural modulus: ASTM D4476 • Crush/impact: ASTM D1709 • Grease/oil resistance: TAPPI Test Method T 559 cm-12 Grease resistance test for paper and paperboard • Thermal conductivity: ISO 8302, GB 10297 • Moisture content: ISO 2017.287, TAPPI, T.2004. 412 om-02 • Vapour transfer: ASTM E96-95 • Food migration: EN 1186 • Biodegradability/compostability: ASTM D 5338, ASTM D6400, EN 13432, EN 14995, ISO 14855, ISO 17088, BS ENV807
SW 205 – Waste gypsum from chemical industries	Sulphur	Gypsum products	Sulphur with purity between 96 – 99%[518]
SW 321 – Rubber or latex wastes	Rubber	Rubber products	• ASTM D 2000 (Specifications for Rubber Materials) • ASTM D 5603 (Standard Classification for Rubber Compounding Materials – Recycled Vulcanizate Particulate Rubber) • IS 7490 Reclaimed Rubber (India)

4.4 SIRIM ECO-LABELLING MARK

Products that are manufactured from recovered materials of the scheduled wastes can be certified under the SIRIM Eco-Labelling Scheme. The SIRIM Eco-Labelling Mark serves as a method to inform consumers or potential customers about a product's environmental advantages, assisting in their purchasing decisions based on environmental safety attributes.

Under the SIRIM Eco-Labelling Scheme, products undergo independent testing and verification against specific eco-label criteria and product standards before being authorised to use the mark on the product, packaging, and promotional materials. More information on the SIRIM Eco-Labelling Scheme can be referred directly to SIRIM's official website.

[518] See note 406.

5

POLLUTION CONTROL SYSTEMS

CHAPTER 5

POLLUTION CONTROL SYSTEMS

5.1 INTRODUCTION

In the modern industrial landscape, the management of scheduled waste has evolved significantly to meet increasingly stringent environmental regulations and sustainability goals. Scheduled waste, which encompasses a wide range of potentially hazardous materials, necessitates not only effective recovery and reuse technologies but also robust pollution control systems to mitigate their environmental impact. Pollution control systems have emerged as vital components, ensuring that the reuse and recovery of scheduled waste are conducted in an environmentally responsible manner.

This Chapter explores pollution control systems, focusing on their pivotal role in the context of scheduled waste management. The types of pollution control systems covered herein mainly include air pollution control systems and water pollution control systems. Each system plays a crucial part in minimizing the environmental footprint of scheduled waste recovery and reuse technologies, ultimately contributing to the overarching goal of sustainable waste management practices.

5.2 AIR POLLUTION CONTROL SYSTEMS

Air Pollution Control Systems (APCS) are integral components of modern industrial operations, designed to seamlessly integrate with local exhaust ventilation systems. Their primary objective is to maintain a consistent level of performance, including collection rate, capacity, and resistance, throughout daily operations. These systems serve a critical function across various industries by preventing the release of harmful chemicals, vapours, and dust into the environment while simultaneously purifying the air within work environments.

In practice, industrial exhaust and emissions are directed into air pollution control equipment and systems, where they undergo processes aimed at removing or reducing air pollutants. These processes typically include combustion, which involves the destruction of pollutants; conversion, which chemically transforms pollutants into less harmful compounds; and collection, the removal of pollutants from waste air before its release into the environment.

The insights presented here are adapted from the *Guidance Document for Fuel Burning Equipments and Air Pollution Control Systems* published by the Department of Environment. For more comprehensive understanding of APCS and their applications, the aforementioned Guidance Document can be referred, which provides detailed information about the APCS minimum design criteria, design methodology, and instrumentation.

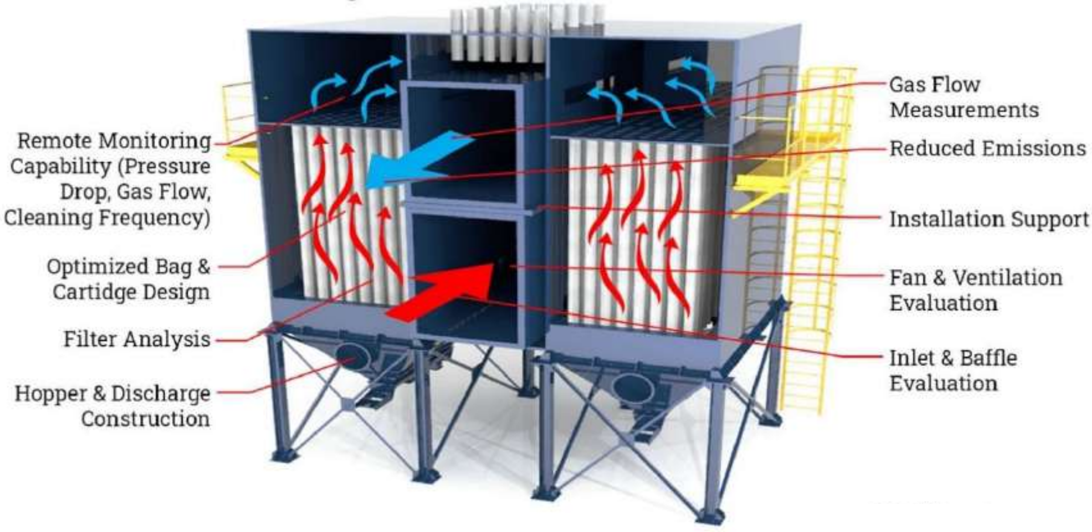
5.2.1 Particulate Collectors

Particulate collectors are essential components of emission control systems designed to reduce the release of total particulate matter into the atmosphere. These devices play a crucial role in maintaining air quality, mitigating environmental impact, and ensuring compliance with stringent regulatory standards. In the following Chapters, key particulate collector technologies are explored.

5.2.1.1 Fabric Filter (Baghouse)

Fabric filtration is widely embraced for the removal of particulates from gas streams, often interchangeably referred to as fabric filters, bag filters, or baghouses. Baghouses, in particular, derive their name from the common cylindrical bag configuration of the fabric used (**Figure 5-1**). In fabric filtration, gas streams laden with dust pass through numerous parallel-hung filter bags, where particulates are captured and subsequently subjected to various cleaning methods.

Figure 5-1: Baghouse[519]



The specific baghouse design hinges on the placement of the draft fan relative to the filter bag. A positive pressure baghouse can either be open to the atmosphere or enclosed, while negative pressure baghouses are exclusively of the closed type. In cases involving gas streams containing hazardous air pollutants that require purification, the closed design is mandated to prevent inadvertent release of trapped pollutants.

Typically, baghouses are constructed from carbon steel, although instances arise where stainless steel is preferred, especially when the gas stream carries high levels

[519] Industrial Quick Search, *Baghouses*, undated.

of sulphur dioxide (SO_2). In such cases, the need for stainless steel can be avoided by insulating the baghouse to ensure the gas stream's temperature remains above its dew point.

Types of baghouses include shaker – cleaning baghouses, reverse air cleaned baghouses, pulse jet filters etc.

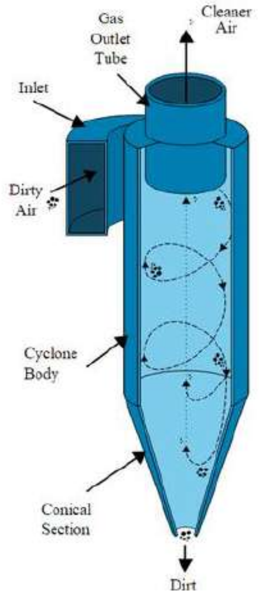
5.2.1.2 Cyclone

Cyclones are a type of initial separator, where they are commonly employed to gather medium-sized and coarse particles. Centrifugal collectors function in a manner similar to initial separators but feature a rotating vane within the collector body, serving to both moving the air and separating the dust.

Air streams with large particles can undergo purification by passing through a cyclone. This dust collection device has low capital and maintenance costs, along with robustness to endure challenging operational conditions. Cyclones are frequently utilized as precleaning units in conjunction with more advanced and costly dust control equipment, such as fabric filters or electrostatic precipitators. It is useful at extracting large and abrasive particulates, reducing the dust load on fabric filters. They find typical applications in wood-working operations, palm oil mills, and the management of grinding and machine dust in tool rooms. Occasionally, multiple cyclones operate in parallel to manage substantial gas stream volumes, referred to as a "multi-cyclone" arrangement.

Cyclones function on the principle of centrifugal force, which is directly proportional to the square of tangential velocity and inversely proportional to the radius of curvature of the gas trajectory (**Figure 5-2**). Consequently, cyclone efficiency increases as device diameter decreases. To attain enhanced efficiencies, cyclones are constructed with smaller diameters. However, this approach is accompanied by the drawback of a rapid escalation in pressure drop as tangential velocity rises. The use of multi-cyclones ensures the achievement of high efficiencies with a moderate pressure drop.

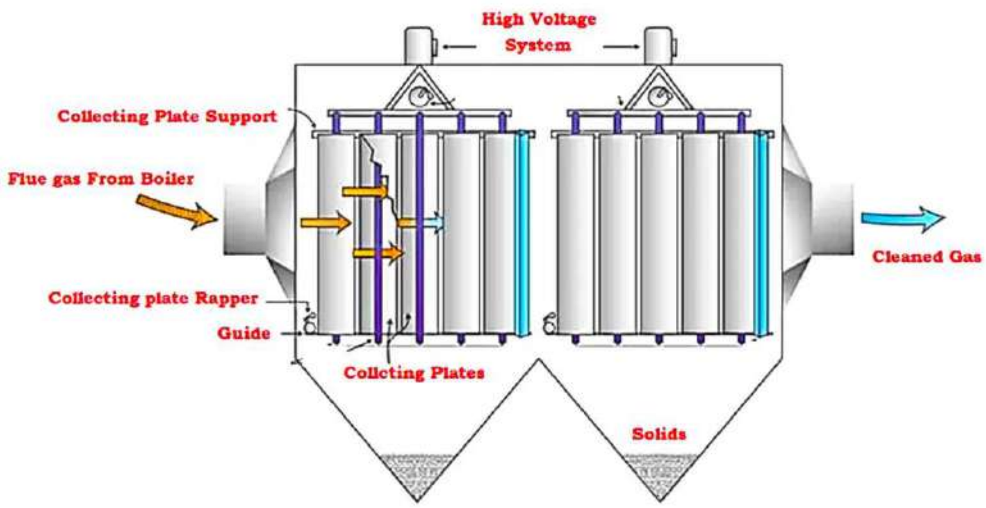
Figure 5-2: Cyclone[520]



5.2.1.3 Electrostatic Precipitator (ESP)

An electrostatic precipitator (ESP) is a large industrial emission control unit that has been utilized in various industries for over 60 years. Its primary purpose is to capture and eliminate dust particles from exhaust gas streams or industrial processes. ESPs excel at collecting fine particles and are considered one of the primary methods for particulate collection in contemporary industrial settings (**Figure 5-3**). They demonstrate versatility by effectively handling substantial volumes across a wide range of inlet temperatures, pressures, dust concentrations, and acidic gas conditions. ESPs can collect particles of various sizes, both in dry and wet states, achieving collection efficiencies that can reach as high as 99% in many industries.

Figure 5-3: Electrostatic Precipitator[521]



[520] Energy Education, *Cyclone separator*, undated.
[521] S Kumar, *Principle of Operation of an Electrostatic Precipitator*, 2023.

ESPs operate based on electrostatic attraction and are prominently used to remove fly ash from gases before discharge. They offer several advantages, including low operating costs, suitability for high-temperature applications (up to 700°C), minimal pressure drops, and exceptionally high particulate (both coarse and fine) collection efficiencies. However, they come with certain drawbacks, such as high capital costs and space requirements.

ESPs can be categorized based on various design features, which comprises of the following:

- The structural design and operation of discharge electrodes (rigid frame, wires, or plates) and collection electrodes (tubular or plates)
- The charging method (single stage or two-stage)
- The temperature of operation (low-temperature or high-temperature)
- The method of particle removal from collection surfaces (wet or dry)

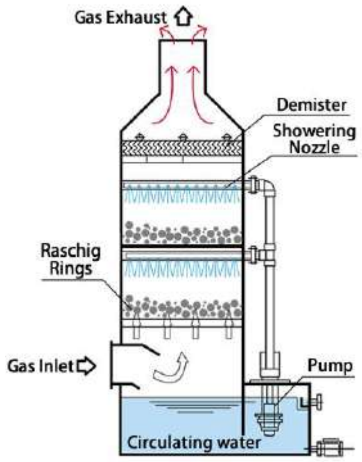
5.2.2 Gas, Vapour and Odour Removers

Gas, vapour, and odour removal equipment plays a vital role in ensuring the safety of working environments. These systems are specifically designed to eliminate or minimize exposure to hazardous gases, noxious vapours, and unpleasant odours that can pose health risks or disrupt operations. The following Chapters will briefly explain on the key technologies used for this purpose.

5.2.2.1 Wet Scrubber

Wet scrubbers are commonly employed as control devices for eliminating gaseous and vapour contaminants (**Figure 5-4**). The removal of these contaminants is achieved through an absorption process that relies on the principles of mass transfer. This absorption process occurs when a liquid, containing concentrations of contaminants below their equilibrium levels, absorbs these contaminants. Broadly categorized, absorption can be either physical or chemical. Physical absorption transpires when contaminants dissolve in an aqueous solvent, while chemical absorption involves the reaction of contaminants with the solvent. The rate of absorption is predominantly influenced by the physical properties of the contaminants and the operating conditions of the wet scrubber unit.

Figure 5-4: Wet Scrubber[522]

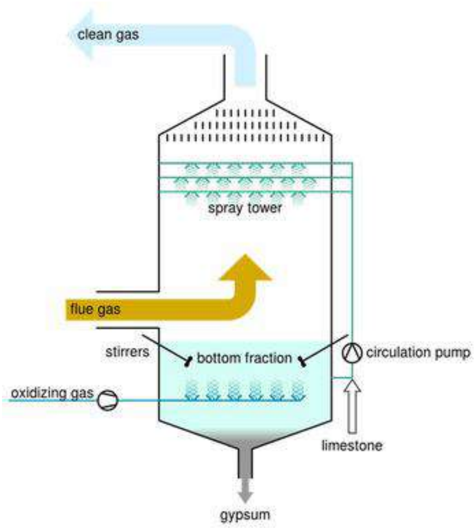


Wet scrubbers come in various types classified based on the direction of contaminant flow, such as countercurrent scrubbers, concurrent scrubbers, and cross-flow scrubbers. They can also be categorized according to design components. For example, a spray tower scrubber is a relatively straightforward absorption chamber equipped with spray nozzles, while a packed tower scrubber employs packing media to enhance mass transfer.

5.2.2.2 Flue Gas Desulphurisation (FGD)

One of the available technologies for controlling the removal of SO_2 from flue gas emissions, is Flue Gas Desulphurisation (FGD) (**Figure 5-5**). FGD systems are generally categorized into two (2) main types: Once-Through and regenerable systems. The distinction between these categories hinges on whether the solution used to absorb SO_2 is recycled.

Figure 5-5: Flue Gas Desulphuriser[523]



[522] Scindia Steam Navigation Company Ltd., *Scrubber*, undated.
[523] Energy Education, *Cyclone separator*, undated.

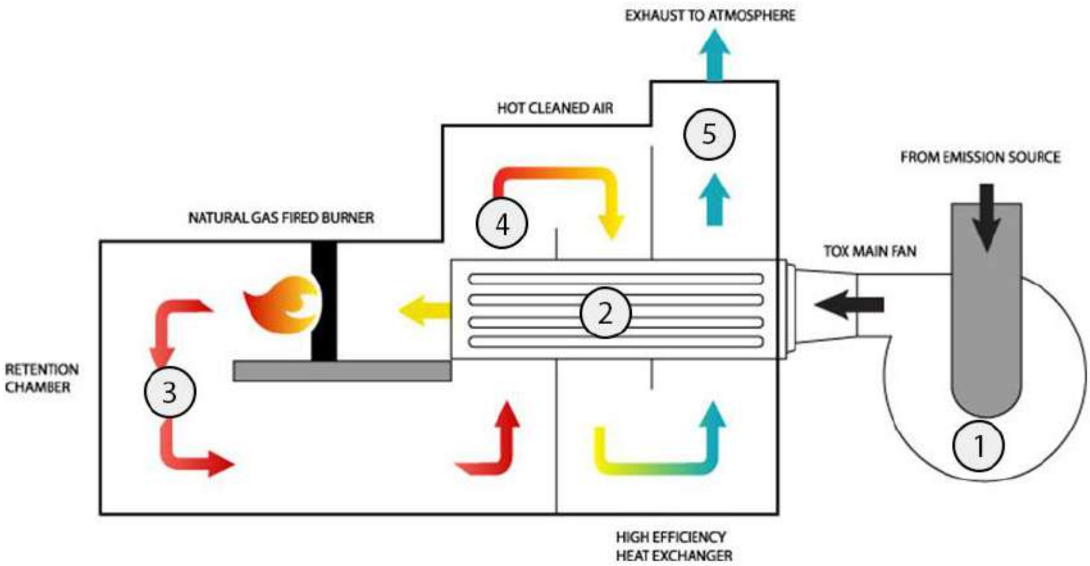
In a Once-Through system, the solution is not recycled, whereas in a regenerable system, the absorbed SO_2 is released and utilized to produce by-products. In the regeneration process, the solution is recycled within the absorber. Additionally, both categories of FGD can be further divided into wet or dry types, which pertain to the form of the absorbent employed in the system. This can involve the use of absorbents in either liquid slurry or dry form.

5.2.2.3 Thermal Oxidizer

Thermal oxidizers are combustion devices that control volatile organic compounds (VOCs), carbon monoxide (CO), and volatile hazardous air pollutants (HAP) emissions by combusting them to carbon dioxide (CO_2) and water (**Figure 5-6**). There are different types of thermal oxidizers, which include direct-fired oxidizers, recuperative oxidizers, and regenerative thermal oxidizers (RTOs).

Air that enters the combustion chamber of the thermal oxidizer is heated to sufficiently high temperature and held at high temperature with turbulence, to ensure the destruction of pollutants. Clean air is then exhausted to the atmosphere.

Figure 5-6: Thermal Oxidizer[524]

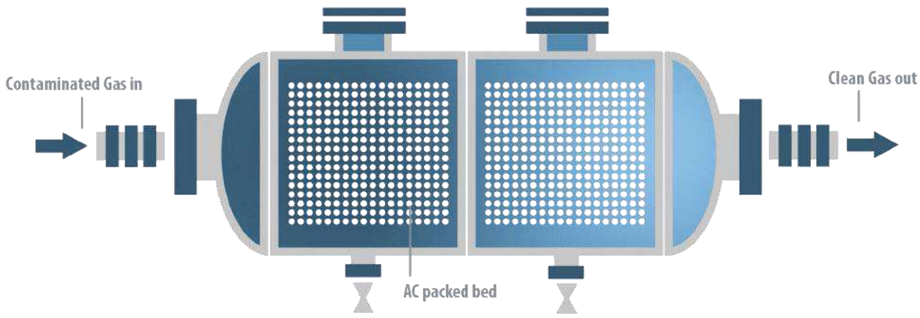


5.2.2.4 Activated Carbon Filter

Activated carbon, known for its vast internal surface area, excels in adsorption. In this process, a gas stream passes through it, and unwanted components bond with the carbon until it is saturated (**Figure 5-7**). Saturated carbon is either replaced or regenerated; in-house regeneration is termed regenerative adsorption.

[524] Kono Kogs, Inc., *What is a Thermal Oxidizer*, 2023.

Figure 5-7: Activated Carbon Filter[525]



Activated carbon is highly effective against VOCs like Benzene, Toluene, Xylene, and more. It is also used for odour and colour removal, with air pre-filtration being common. Regeneration and solvent recovery are cost-effective with high solvent usage. Impregnated carbons selectively absorb specific chemicals.

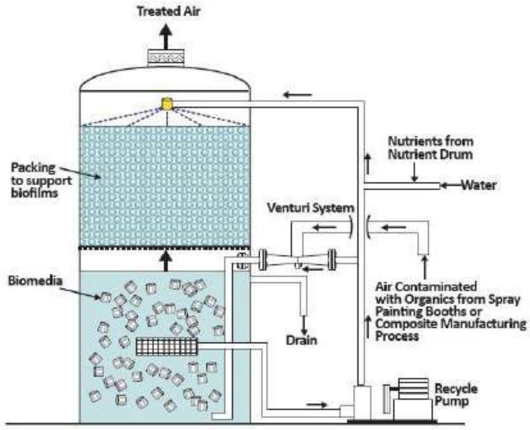
Saturation is typically expressed in g/kg of activated carbon, determined by air contaminant concentration. Around 20-25 g of solvent (as carbon) per 100 g of activated carbon can be adsorbed effectively. Capacity depends on factors like chemical characteristics, concentration, temperature, and polarity. Advantages include frequent replacement, sudden filter failure when saturated, and the risk of spontaneous combustion (e.g., with ketones, turpentines).

5.2.2.5 Biofilter

Biofiltration is a process that degrades VOCs and odourous substances within a biofilter. When pollutants come into contact with the biofilter media, they transition from the air phase to the water phase, forming a thin biological film around each media particle. Bacteria within this film then biologically oxidize the VOCs and odourous compounds, transforming them into carbon dioxide and water (**Figure 5-8**). This organic compound breakdown using bacteria at room temperature is termed Biological Oxidation.

[525] Condorchem Enviro Solutions, *Activated Carbon Filters for VOC, Odour and Hazardous Gas Control*, 2023.

Figure 5-8: Biofilter[526]



The advantages of biofiltration include:

- **Minimal Power Consumption:** Biofilters mainly require two power-consuming components: a recirculation pump for humidification and a fan to draw the gas stream through the equipment.
- **Low Pressure Drop:** Biofilters have a considerably lower pressure drop compared to catalytic or regenerative thermal oxidizers, leading to energy savings in fan power consumption.
- **Environmental Benefits:** Biofiltration results in zero NOx emissions, substantially reduced carbon dioxide emissions, and has very few moving parts, leading to lower maintenance costs.

5.2.2.6 Fume Hood

A fume hood, also known as a fume cupboard, is a specialized local ventilation device designed to minimize exposure to harmful or toxic fumes, vapours, or dust. There are two primary types of fume hoods: ducted and recirculating (also known as ductless). Fume hoods primarily protect the user and are commonly employed in laboratories where hazardous or noxious chemicals are generated during testing, research, development, or teaching. They are also utilized in industrial settings and other activities where dangerous or noxious vapours, gases, or dusts are produced.

Most fume hoods are configured to connect to an exhaust system that expels the air directly to the exterior of a building. This process demands significant energy to operate the exhaust system, as well as to condition, filter, control, and circulate the replacement air that enters the space after the exhaust.

5.3 WATER POLLUTION CONTROL SYSTEMS

Water pollution control systems play a pivotal role in the responsible management of scheduled waste. These systems are primarily employed for treating industrial

526 McRae Engineering Equipment Limited, *Biofilters*, 2019.

effluents, ensuring that the discharged water meets stringent environmental standards and regulatory requirements. In essence, they serve as essential components of the overall strategy for the reuse and recovery of scheduled waste.

These systems are specifically designed to efficiently remove contaminants, pollutants, and hazardous substances from the effluents during scheduled waste recoveries, rendering it safe for discharge or potential reuse. The common system that are utilized by scheduled waste recovery facilities are industrial effluent treatment systems. By adopting advanced technologies and treatment processes, these treatment systems help to minimize the ecological footprint of these reuse and recovery operations.

In the treatment of industrial effluents, there are three (3) primary technology categories: physical, chemical and biological methods. The selection of the most suitable treatment method primarily hinges on the specific pollutants that need to be eliminated. The following Chapters provide summaries of three (3) treatment processes sourced from the *Industrial Waste Treatment Handbook (Second Edition)* by Woodard & Curran, Inc., published in 2006 and the *Guidance Document on the Design and Operation of Industrial Effluent Treatment Systems* published by the Department of Environment, Malaysia, in 2009.

The design and operation of Industrial Effluent Treatment Systems should adhere to the guidelines outlined in the *Guidance Document on the Design and Operation of Industrial Effluent Treatment Systems* (2009).

5.3.1 Physical Treatment Processes

Industrial effluent treatment through physical methods relies on natural forces like gravity, electrical attraction, and van der Waals forces, as well as the use of physical obstacles to remove contaminants. Typically, these mechanisms do not induce any chemical alterations in the target substances. Instead, they may alter the physical state, such as vaporisation, or bring about the aggregation of dispersed particles, which occurs during filtration.

Physical industrial effluent treatment methods encompass processes such as sedimentation, flotation, and adsorption, in addition to employing barriers like bar racks, screens, deep bed filters, and membranes. These techniques primarily rely on physical phenomena and structures to achieve the removal of contaminants from wastewater streams.

5.3.2 Chemical Treatment Processes

Chemical industrial effluent treatment methods harness two (2) key properties: first, the chemical characteristics of pollutants, which determine their tendency to react or interact with treatment chemicals; and second, the chemical characteristics of the reaction products formed between pollutants and treatment chemicals, including their solubility, volatility, or other attributes related to their ability to stay in water solution or suspension.

Generally, there are six (6) chemical processes that can be employed to eliminate substances from wastewater:

- Inducing reactions that lead to the formation of insoluble solids;
- Inducing reactions that result in the production of insoluble gases;
- Reducing surface charges to trigger the coagulation of colloidal suspensions;
- Promoting reactions that transform non-biodegradable substances into biologically degradable ones;
- Initiating reactions that neutralize or render chelating agents ineffective; and
- Carrying out oxidation or reduction reactions to generate non-hazardous substances or substances that can be more easily removed using one of the methods mentioned earlier.

5.3.3 Biological Treatment Processes

Biological treatment processes are integral for the removal of dissolved organic matter from industrial effluents, targeting the reduction of complex organic compounds often measured as COD and BOD. These processes can be categorized into two (2) main types: suspended growth systems and attached growth systems. Suspended growth systems, such as the activated sludge process, involve microorganisms suspended in industrial effluent, breaking down organic matter in a mixed liquor before separating it from biomass. In contrast, attached growth systems, like trickling filters and rotating biological contactors, cultivate microorganisms in biofilms on solid media, where industrial effluent trickles over the biofilm for pollutant degradation.

In Malaysia, aerobic biological treatment processes, which depend on dissolved oxygen to support microorganism metabolism, is more commonly used. These aerobic processes are highly efficient in reducing organic pollutants and are favoured for their adaptability to various industrial effluent types.

5.4 OTHER POLLUTION CONTROL SYSTEMS

The above Chapters provide an overview of pollution control systems, with a particular focus on air and water pollution control methods. However, it is crucial to acknowledge that pollution control extends beyond these domains. Various environmental aspects, such as fugitive emissions, noise levels and vibrations, also demand careful consideration when implementing reuse or recovery technologies to manage scheduled waste.

In practice, this means that those responsible for implementing these technologies shall assume a comprehensive role in safeguarding the environment. This entails not only addressing air and water pollution but also attending to all relevant facets of environmental conservation and protection. Therefore, while the summaries above serve as a valuable starting point, they should be viewed as part of a broader spectrum of responsibilities to ensure the sustainable and responsible use of technology.

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GLOSSARY

GLOSSARY

British Standards (BS)	Britain's National Standards which are controlled by the British Standards Institute (BSI).
British Standards incorporating a European Standard (BS EN)	European standards are aimed at facilitating commerce between the countries of the European community. As a necessity they are a compromise between the different national standards. Once a European Standard has been agreed it supersedes any existing national standard and becomes the new national standard. In Britain these Standards are then prefixed with BS EN.
Circular Economy	A systems solution framework that tackles global challenges like climate change, biodiversity loss, waste and pollution. It is based on three design driven principles: eliminate waste and pollution, circular products and materials, and regenerate nature.
Co-Processing	The use of suitable waste material in manufacturing processes for the purpose of energy and/or resource recovery, and resultant reduction in the use of conventional fuels and/or raw materials through substitution.
Cradle-to-cradle	A design concept that emphasizes creating products and systems that are restorative and regenerative, with the aim of cycling indefinitely without creating waste or pollution.
Cradle-to-grave	A safe waste management principle which controls subject waste throughout its lifecycle: from generation, collection, storage, transportation, treatment, recovery to disposal. It takes into account the priority order for waste management in terms of resource utilization without compromising environmental and human health.
Electronic Scheduled Waste Information System (eSWIS)	An online system acting as an environmental mainstreaming tool for guided self-regulation. This system is used to facilitate periodical reporting of waste generation, inventory, movement and handling of scheduled waste in compliance to the national regulations.

Energy Recovery	Conversion of waste materials into usable heat, electricity or fuel.
Environmentally Sound Management (ESM)	A waste management approach that prioritizes environmental protection and human health. It involves taking all practicable steps to ensure that hazardous wastes or other wastes are managed in a manner which will protect human health and the environment against the adverse effects which may result from such wastes.
KAOFIN Process	Patented agglomeration process for the production of a floor absorbent in the form of a granular product
Material Recovery	Recovery operations including preparing for re-use, recycling and backfilling. Does not include energy recovery or reprocessing of materials that are to be used as fuels or other means to generate energy.
Malaysian Standard (MS)	Malaysian Standard (MS) is a consensus document developed by Standards Development Committee (SDCs) within the Malaysian Standards Development System and approved by the Minister of International Trade and Industry in accordance with Standards of Malaysia Act 1996 [Act 549]. An MS is a technical document that specifies the minimum requirements of quality and safety for voluntary use by the public. The MS becomes mandatory when a regulatory agency enforces its use through the relevant Act and Regulations.
Malaysian Standard incorporating a European Standard (MS EN)	As Malaysia has limited research and development capability in developing codes of practice and furthermore has always used the British Standards as the main source of reference for structural design, it would be prudent to follow suit the UK in practicing the Eurocode. Through the Department of Standards Malaysia (Standards Malaysia), the adopted Malaysian Standard is identical with European Standard without alteration as to oblige with the European Committee for Standardization (CEN) regulations.
Pipco Process	Process for recovery of sulphur values from a gas stream patented by Pipco Inc.
Reduce	Measures to be taken before a substance, material or product has become waste.

Reuse	Using again of products, object and substance for the same or alternative purposes for which it was conceived that promotes resource efficiency without the necessity of pre-processing. Types of registered disposal operation includes: • Special management for use as fertilizer/soil conditioner • Special management for use as neutralizing agent • Special
Recycle	Operations by which waste materials are reprocessed into products, materials and substances, whether for the original or other purposes. It does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling. In this Guidance document, this term will be included under the "Recovery" umbrella.
Recovery	Operations where waste is serving a useful purpose by replacing other material which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy. This includes material recovery/reclamation, energy recovery and reprocessing into materials that are to be used as fuels or other means to generate energy.
Final Disposal	Operations that result in final disposition, placement or destruction of waste, which is not recovery even where the operation has secondary consequence the reclamation of substances or energy.
Secure landfill	Premises occupied or used for the disposal of any scheduled waste on land.
Scheduled Wastes	Any waste falling within the categories of waste listed in the First Schedule of the Environmental Quality (Scheduled Wastes) Regulations 2005. The schedule consists of 77 waste types compartmentalized into five material characteristics.

Special Management	A provision under Regulation 7 of the Environmental Quality (Scheduled Wastes) Regulation 2005, where a waste generator may apply in writing to have the scheduled wastes generated from their particular facility or process excluded from being treated, disposed of or recovered in premises or facilities other than at the prescribed premises or on-site treatment or recovery facilities.
Storage	The holding of scheduled waste for a temporary period prior to the waste being transported, treated and disposed.
TAK System	Asphalt rubber system developed in 1986 by H. Barry Takallou to produce an asphalt concrete composition made up of a coarse crumb rubber, a fine crumb rubber, asphaltic binder, and mineral aggregate.
Technology Readiness Levels (TRLs)	A measurement system used to assess the maturity level of a particular technology throughout its research, development and deployment phase progress.
Toxicity Characteristics Leaching Procedure (TCLP)	TCLP is required for Federal hazardous waste characterization, which is used to simulate a landfill environment and to determine how much of a regulated compound will leach out into the environment.
Total Threshold Limit Concentration (TTLC)	TTLC is a California requirement for hazardous to determine the total amount of a compound in the sample.
Treatment	Processing operations that change the biological or physico-chemical properties of waste, including interim operations which prepare waste prior to reuse, recovery or final disposal operation.
Trial burn	Used as the basis for establishing allowable operation limits for co-processing. Emissions testing performed for demonstrating compliance with the destruction and removal efficiency and destruction efficiency performance standards and regulatory emission limits.
Waste	Anything that the holder discards, intends to discard, or is required to discard by the provisions of the national law.
Waste Characteristics (WC)	Characteristics of waste that exhibit any one or more of the following characteristic properties; ignitability, corrosivity, reactivity, or toxicity.

Waste Acceptance Criteria (WAC)	Technical and administrative requirements that a waste shall meet in order to be accepted at a waste management facility or undergo further treatment or processing.
Waste Hierarchy	A ranking system for material and waste management options based on their resource efficiency in terms of reduction or prevention of waste generation, reduction of the overall impact from waste generation, and subsequent management of waste. It gives material and waste priority to prevention, followed by preparing for reuse, recycling, recovery and ends with disposal.
Waste Management	The collection, transportation, recovery and final disposal of waste, including the supervision of such operations and the after-care of disposal sites, and including actions taken as a waste generator or waste receiver.
Physical Management Method	Relies on the physical characteristics of the waste materials in order to separate the hazardous constituents in a waste stream, wherein residues are further treated and ultimately sent for disposal or precious materials are recovered and separated from the stream.
Chemical Management Method	Using chemical reagents to change the chemical structure of the constituents, which produces residues that are less hazardous than the original waste generated or recover material from the waste materials.
Biological Management Method	Microorganisms degrade or detoxify the hazardous waste components present, to less harmful products, or decomposition of unwanted components of the waste material to form an alternative raw material, through metabolic processes that can occur in water, soil, or air phases.
Thermal Management Method	Volume and toxicity of the wastes are reduced significantly using high temperature, at the same time recovering materials that will not be decomposed by high heat and generating energy or fuel in the process.

APPENDIX A
Application for the Importation of Scheduled Waste into Malaysia (AS 14 (Rev 2006) Form)

Borang AS 14 (Rev. 2006)

AS 14 (Rev. 2006) Form

PERMOHONAN UNTUK MENGIMPORT BUANGAN TERJADUAL KE DALAM MALAYSIA

APPLICATION FOR THE IMPORTATION OF SCHEDULED WASTE INTO MALAYSIA

SILA HANTAR KEPADA:
PLEASE SUBMIT TO:

Jabatan Alam Sekitar
Kementerian Sumber Asli dan Alam Sekitar
Aras 1 - 4,Podium 2 & 3
Lot 4G3, Presint 4
Pusat Pentadbiran Kerajaan Persekutuan
62574 PUTRAJAYA

Talian Umum : 03 - 8871 2000 / 8871 2200
Faks : 03 - 8889 1973 / 8888 6120
JASLINE : 1-800-88-2727

www.doe.gov.my

APPLICATION FOR WRITTEN PERMISSION FOR THE IMPORTATION OF SCHEDULED WASTES UNDER SECTION 34B ENVIRONMENTAL QUALITY ACT, 1974
AS 14 (Rev. 2006) Form

A. CONSIGNOR/EXPORTER DETAILS	D. IMPORT DETAILS
1. ROB/ROC No: (Optional)	*1. Mode of Transport (Maritime/Rail/Road/Air/Post):*
2. Company Name & Address:	*2. Purpose (Private/Business/Research/Exhibition/Others):*
	3. Country of Origin:
	4. Place (Name of Port) of Origin:
3. Contact Person:	*5. Consigned from:*
4. Tel No.:	
5. Fax No.:	*6. Place of Import (State in Malaysia):*
B. CONSIGNEE/IMPORTER DETAILS	
1. ROB/ROC No:	*7. Location of Import (Port of Entry in Malaysia):*
2. Company Name & Address:	*8. Customs Station (in Malaysia):*
	E. SCHEDULED WASTE (SW) DETAILS
	1. SW Code (all digit): *SW* ☐☐☐ - ☐☐ - ☐☐☐
	2. SW Description (as stated in E.1):
3. Contact Person:	
4. Tel No.:	*3. Malaysian Customs Tariff (all digit):* *H.S.* ☐☐☐☐☐☐☐☐☐☐
5. Fax No.:	
C. APPLICANT DETAILS	*4. Item Description (as stated in E.3):*
1. Applicant Name:	*5. Total Quantity Based on Customs Tariff Unit:*
2. Applicant I.C./Passport No.:	*6. Unit Cost C.I.F. (RM):*
	7. Total Value C.I.F. (RM):
3. Applicant Designation:	*8. Waste has been imported before (Yes/No) & Year:*

F. SW TRANSPORT CONTRACTOR	FOR OFFICIAL USE
1. Company Name:	**Permit No.:**
2. Company Address:	***DOE Cert. No. :***
3. Valid DOE License No.:	***Date of Expiry :***
G. CONFIRMATION OF DETAILS	
I certify that the information provided above is true.	
Date: *Signature of Applicant:*	*(Signature & Official Stamp)*
Name:	*Name:*
I.C. No.:	*for the Director-General of Environment Malaysia*

Note: All the above information must be fully completed in order to process the application.

CHECKLIST FOR THE IMPORT APPLICATION

No.	Subject	Yes (√)	Remarks
1.	*Cover letter for the Application*		
2.	*AS 14 (Rev. 2006) Form*		
3.	*Company Profile of the Waste Generator*		
4.	*Company Profile of the Importer/End-User*		
5.	*Company Registration Certificate (ROC/ROB) of Importer/End-User*		
6.	*Certified Copy of I.C. or Passport of the Applicant*		
7.	*Land Transporter (Copy of License by DOE)*		
8.	*Contractual Agreement (original):* *Waste Generator + Importer/End-User + Transporter*		
9.	*Information on the waste:* *- source of waste (please mark in the flowchart)* *- lab analysis* *- inventory (for the last 3 years)* *- total quantity of waste imported, quantity of each import & number of shipments* *- history of quantity of waste that has been imported for the last 3 years, last year & last month*		
10.	*Justification for import*		
11.	*Written Approval & License issued by DOE for the waste*		
12.	*Bank Guarantee (original) - RM10,000*		
13.	*Emergency Response Procedure (ERP)*		
14.	*Technical information on the waste recovery/reuse/recycle process*		
15.	*Complete process/flowchart of item 13*		
16.	*Percentage on residue generated from the above process (item 13) and its further disposal*		
17.	*Notification letter from the Competent Authority of the exporting country*		

Note:

- ***The entire documents above are compulsory to be submitted to DOE HQ for processing application.***

APPENDIX B

Application for the Export of Scheduled Waste from Malaysia (AS 15A (Rev 2006) Form)

Borang AS 15A (Rev. 2006)

AS 15A (Rev. 2006) Form

PERMOHONAN UNTUK MENGEKSPORT BUANGAN TERJADUAL DARI MALAYSIA

APPLICATION FOR EXPORT OF SCHEDULED WASTE FROM MALAYSIA

SILA HANTAR KEPADA:
PLEASE SUBMIT TO:

Jabatan Alam Sekitar
Kementerian Sumber Asli dan Alam Sekitar
Aras 1 - 4, Podium 2 & 3
Lot 4G3, Presint 4
Pusat Pentadbiran Kerajaan Persekutuan
62574 PUTRAJAYA

Talian Umum : 03 - 8871 2000 / 8871 2200
Faks : 03 - 8889 1973 / 8888 6120
JASLINE : 1-800-88-2727

www.doe.gov.my

APPLICATION FOR WRITTEN PERMISSION FOR THE EXPORT OF SCHEDULED WASTES UNDER SECTION 34B, ENVIRONMENTAL QUALITY ACT, 1974
AS 15A (Rev. 2006) Form

A. CONSIGNOR/EXPORTER DETAILS	**D. APPLICANT DETAILS**
1. ROB/ROC No:	*1. Applicant Name:*
2. Company Name & Address:	*2. Applicant I.C./Passport No.:*
	3. Applicant Designation:
	E. SCHEDULED WASTE (SW) DETAILS
	1. SW Code (all digit): SW [ ][ ][ ] - [ ][ ] - [ ][ ]
	2. SW Description (as stated in E.1):
3. Contact Person:	
4. Tel No.:	*3. Malaysian Customs Tariff (all digit):* H.S. [ ][ ][ ][ ][ ][ ][ ][ ][ ]
5. Fax No.:	
B. CONSIGNEE/IMPORTER DETAILS	*4. Item Description (as stated in E.3):*
1. ROB/ROC No: (Optional)	*5. Quantity Based on Customs Tariff Unit:*
2. Company Name & Address:	*6. Unit Cost C.I.F. (RM):*
	7. Total Value C.I.F. (RM):
	8. Waste has been export before (Yes/No) & Year:
3. Contact Person:	
4. Tel No.:	**F. SW TRANSPORT CONTRACTOR**
5. Fax No.:	*1. Company Name:*
C. EXPORT DETAILS	
1. Mode of Transport (Maritime/Rail/Road/Air/Post):	*2. Company Address:*
2. Date of Export:	*3. Valid DOE License No.:*
3. Country of Origin:	**G. DETAIL ON COST WASTE MANAGEMENT**
4. Place of Origin (State in Malaysia):	*(i) Export management (Transport/storage/port charges)* :RM
5. Port of Export (in Malaysia):	*(ii) Fix/Handling cost* :RM
6. Customs Station (in Malaysia):	*(iii) Treatment cost* :RM
7. Country of Final Destination:	*(iv) Recovery obtainable* :RM
8. Port of Discharge:	*TOTAL* :RM
H. CONFIRMATION OF DETAILS	**FOR OFFICIAL USE**
I certify that the information above is true *Date:* *Signature of Applicant:* .... *Name:* *I.C. No.:*	***Permit No. :*** ***DOE Cert. No. :*** ***Date of Expiry :*** *(Signature & Official Stamp)* *Name:* *for the Director-General of Environment Malaysia*

Note: All the above information must be fully completed in order to process the application.

CHECKLIST FOR THE EXPORT APPLICATION

No.	***Subject***	***Yes (√)***	***Remarks***
1.	*Cover letter for the Application*		
2.	*AS 15A (Rev. 2006) Form*		
3.	*'Transboundary Movement of Waste Notification Form' (Basel Convention: Revised 2011)* *http://www.basel.int/Procedures/NotificationMovementDocuments/tabid/1327/Default.aspx*		
4.	*Company Profile of the Waste Generator*		
5.	*Company Profile of the Consignee/Receiver*		
6.	*Company Profile of the Facility Operator* *- process/disposal* *- licensed/approved by the competent authority* *- liability*		
7.	*Land transporter (Copy of License by DOE)*		
8.	*Contractual Agreement (original):* *Waste Generator + Facility Operator + Transporter*		
9.	*Information on the waste:* *- source of waste (please mark in the flowchart)* *- lab analysis* *- inventory (for the last 3 years)*		
10.	*Justification for export* *(For SW110 export: Study On Technology Comparison by local and intended recovery facilities)*		
11.	*Bank Guarantee (original) - RM 25,000*		
12.	*Insurance Coverage*		
13.	*Emergency Response Procedure (ERP)*		
14.	*Shipment Schedule, route*		
15.	*Technical information on the waste recovery process*		
16.	*Flowchart of the recovery process, photographs, pamphlet*		
17.	*Declaration on the waste component to be recovered*		
18.	*Percentage on residue generated from the recovery process and its further disposal*		
19.	*Past experience on waste recovery (facility operator)*		
20.	*Cost estimation (transportation, recovery process, recovery obtainable)*		

Note:

- ***The entire documents above are compulsory to be submitted to DOE HQ for processing application.***
- ***Please submit a complete copy for DOE, import country and transit countries.***

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