



# **Incorporation of plasterboard waste into construction materials**

## **A literature review**

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## Abstract

Plasterboard (or gypsum board) is now an indispensable building material globally due to its lightweight, low-cost, fire resistance, acoustic insulation, and ease of use. However, this extensive use has raised critical sustainability issues. Plasterboard disposal plays a major role in landfills due to waste disposal, and gypsum decomposed in anaerobic conditions produces hazardous hydrogen sulfide emissions, threatening human health, air quality, soil health, and groundwater. With global construction waste projected to rise considerably over the next several decades, the ecological burden of plasterboard production and disposal is, therefore, urgent.

To begin, this thesis will conduct a dedicated systematic literature review to consolidate this fragmented knowledge base regarding plasterboard's lifecycle implications, particularly in terms of raw material extraction, mechanical and functional performance, waste build-up, and second use. This thesis focuses on synthesizing peer-reviewed studies, grey literature produced by manufacturers, industry collection, and international case studies, to assess environmental challenges, policy impediments, and technological developments. This review will synthesise the synthetic knowledge on recycling gypsum, as manufacturing closed-loop internal plasterboard, producing hybrid composites containing ceramic residues, reusing in the agricultural supply chain or in geotechnical applications, can save 70% energy in producing greenhouse gases, reduce energy consumption by more than 40%, and divert a considerable volume of waste streams from landfill. However, there are significant barriers to large-scale adoption in waste management, particularly in developing countries with limited waste solution features around this material usage.

Using a demanding comparative study of the case studies conducted internationally, the proposed research determines the best practices in circular economic integration, with a strong emphasis on the importance of specific regulatory frameworks, public-privately working together, and eco-innovation in transforming plasterboard into a sustainable construction material, rather than a linear consumption product. The study argues that the alignment between technological advances and policy implementation and industrial responsibility is indispensable in balancing the growth of the construction industry and the conservation of the environment. The results therefore contribute to the academic literature as well as providing practical information to engineers, policy makers and industry leaders to reduce the environmental effects of construction materials in Europe and the rest of the world.

**Keywords:** Plasterboard, Lifecycle Assessment, Environmental Impact

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# Chapter I Introduction

The past few decades have seen a phenomenal rise in plasterboard (gypsum board) as a building material as the construction industry has found it cheap, lightweight and versatile. Although plasterboard does have many technical benefits such as fire resistance, soundproofing and ease of assembly, there is mounting pressure on environmental sustainability due to the extensive application of it. Plasterboard waste has emerged to become a major waste material of construction and demolition worldwide raising serious concerns to the capacity of the landfills, the quality of air in the country and the health of the soil and water through hazardous plasterboard components commonly including gypsum and synthetic additives (Yuan & Shen, 2011).

With the demand to promote sustainable construction and the implementation of the concept of the circular economy, the life cycle implications of using and disposing of plasterboard have increased (European Environment Agency (EEA), 2020). Even though some technological enhancements have emerged to enhance better recycling of plasterboard, the implementation of the solution has been poor in certain states and industries because of compliance, cost, and other logistical challenges (Pacheco-Torgal et al., 2013).

The proposed thesis seeks to undertake an extensive literature review that consolidates existing studies pertaining to the use, disposal and recycling of plasterboard. Presented in the form of a systematic review of peer-reviewed journals, industry publications, and global case studies, this analysis discusses the environmental impacts of plasterboard waste, analyses the available mitigation measures, and points to promising techniques to maximize the eco-friendly potential of the material in post-construction life (Cuccagna & Mignot, 2024).

This thesis aims to identify a number of crucial gaps in the literature, evaluate the success of the proposed solutions, address gaps in the existing knowledge base on this subject by consolidating the disjointed knowledge on this topic in order to contribute to a more comprehensive view of the environmental impact of plasterboard and ways in which they can be recovered. The results will assist researchers and policymakers (including industry professionals) to embrace more sustainable waste management practices in the construction industry.

## **I.1 Methodology of Literature Review**

### **I.1.1 Methodological Approach**

Since this thesis is based entirely on secondary data, the research follows a systematic literature review methodology. This approach enables the identification, evaluation, and synthesis of relevant academic and technical publications related to plasterboard use, environmental impact, and recycling innovations.

### **I.1.2 Data Sources**

To ensure a comprehensive and credible foundation, literature was collected from the following primary citation:

- Peer-reviewed academic journals (e.g., Journal of Cleaner Production, Waste Management, Construction and Building Materials)
- Scientific databases: ScienceDirect, Scopus, SpringerLink, Google Scholar
- Government and NGO reports (e.g., CSIRO, EU Waste Framework Directive)
- Industry white papers and technical reports from manufacturers and recycling companies
- Life Cycle Assessment (LCA) case studies

### **I.1.3 Search Strategy and Keywords**

Keyword combinations were developed to capture diverse perspectives on the topic. Common keywords and Boolean operators used included:

- "Plasterboard waste" OR "gypsum board recycling"
- "Construction and demolition waste" AND "environmental impact"
- "Gypsum lifecycle" OR "LCA of plasterboard"
- "Sustainable construction materials" OR "circular economy in construction"
- "Fire resistance of gypsum" OR "soundproofing plasterboard"
- "Recycled gypsum" AND "mechanical properties"

**I.1.4 Inclusion and Exclusion Criteria**

Inclusion Criteria:

- Studies published between 1888 and 2025
- Articles written in English
- Research focused on environmental impacts, recycling techniques, mechanical properties, and second-life applications
- Studies using quantitative, qualitative, or mixed methodologies

**I.1.5 Data Analysis and Synthesis**

The selected literature was analyzed using a thematic synthesis approach. The findings were organized into key thematic categories aligned with the chapter structure of this thesis:

1. Overview of Plasterboard Composition and Use
2. Climate Change and Waste Accumulation
3. Environmental Impact of Plasterboard Waste
4. Second life for plasterboard

# Chapter II: Overview of Plasterboard Use and Disposal

## II.1 Introduction

This chapter provides an overview of plasterboard use in construction, including its background and history. It investigates major elements and additives that affect the physical and mechanical performance of plasterboard. Particular attention is given to its manufacturing processes as well as its fire resistance, soundproofing, and thermal insulation characteristics. Understanding the technical performance and lifecycle of plasterboard forms the basis for evaluating its environmental performance and options for sustainable disposal or reuse, which are the focus of the subsequent chapters.

## II.2 Historical Development of Plasterboard

Gypsum was used approximately 7000 B.C. as a floor material. Manufacturing gypsum-based products began industrially in 1888 when Augustine Sackett designed a machine to create drywall panels by putting gypsum in-between two sheets of paper. Manufacturing was further developed in 1908 by Stephen Kelly when he modified the machine with a single sheet of paper on both sides of the gypsum. (Eurogypsum, 2015)

In 1901 a gypsum board manufacturing plant was established in the United States, and this started the process of large-scale production. The usage of gypsum spread to Europe in 1917 with the first factory built in Liverpool. Now, there are more than 200 factories producing gypsum boards in North America and Europe. Eurogypsum (2015) estimates the yearly demand for gypsum-based products, including drywalls, blocks, and plasters will exceed 500 million square meters in Europe.



Figure 1. Gypsum Applications for: a) Ceilings and b) Decorative Plaster

### II.3 Material Composition and Properties

#### II.3.1 Gypsum Core (Natural vs. Synthetic)

Gypsum (calcium sulfate dihydrate) is a naturally occurring mineral with the chemical formula  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ . It is widely valued in construction for its fire resistance, sound insulation, and ease of workability when used in plasterboard. Gypsum can be sourced both naturally and synthetically, with each type contributing unique qualities to the material.

Naturally occurring gypsum primarily is extracted in the United States, Canada, Mexico, Iran and China. Evaporite-rich geographic areas contain the biggest gypsum deposits that form because ancient ocean waters evaporate during the process. The purity level of naturally occurring gypsum spans between 80% to 95% yet high-purity gypsum remains superior when making cores that both remain stable and resist deterioration (Eurogypsum 2008, U.S. Geological Survey, 2024; ASTM International, 2020). The mining process to obtain gypsum leads to major environmental harm through open-pit mining procedures that degrade landscapes, harm biodiversity and release dust into the atmosphere. Some gypsum mines

introduce reclamation techniques to reconstruct landforms and vegetation after mining operations since these actions decrease environmental damage.

While FGD (Flue Gas Desulfurization) gypsum or synthetic gypsum serves as an industrial output from power plants which extract sulfur from smoke exhausts to decrease environmental contaminants. Its chemical makeup overlaps (European Commission, 2018) closely with natural gypsum thus making it work as a popular replacement in multiple applications. The high levels of purity in synthetic gypsum reach 98% because the manufacturing environment is carefully controlled during production (European Commission, 2018). Synthetic gypsum supports environmental sustainability by offering a recycling framework for industrial waste materials while easing the demand for mining operations and preserving natural resources along with decreasing industrial waste volumes. The manufacturing process of synthetic gypsum depends on coal-fired power facilities, yet this creates environmental problems because coal operations emit greenhouse gases and air pollutants thereby challenging its permanent viability. as shown in Table 1.

**Table 1. Comparison of Natural Gypsum and Synthetic (FGD) Gypsum**

Aspect	Natural Gypsum	Synthetic (FGD) Gypsum
<b>Source</b>	Naturally occurring mineral extracted from sedimentary deposits in regions such as the U.S., Canada, Mexico, Iran, and China.	By-product of flue gas desulfurization processes in coal-fired power plants.
<b>Chemical Formula</b>	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ (Calcium sulfate dihydrate).	Chemically identical: $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ .
<b>Purity Range</b>	80–95% depending on deposit and geological formation.	Up to 98% due to controlled industrial conditions.
<b>Environmental Impact</b>	Mining can cause dust emissions, biodiversity loss, and land degradation; reclamation can reduce impact.	Reduces mining demand and recycles industrial waste but depends on coal-based energy systems.
<b>Sustainability Aspect</b>	Non-renewable mineral resource requiring restoration of mined land.	Promotes circular economy by reusing industrial by-products.

**Note.** This table compares key aspects of natural and synthetic (FGD) gypsum, including source, chemical composition, purity, environmental impact, and sustainability considerations.

Synthetic gypsum is chemically identical to natural gypsum but is a by-product of coal-fired power plants, raising concerns about long-term sustainability. References: U.S. Geological Survey (2024); ASTM International (2020); European Commission (2018) Eurogypsum 2008.

Uses of natural or synthetic gypsum in the industry base on available resource availability and government requirements. People consider synthetic gypsum as the more sustainable material because it helps reduce environmental impacts by allowing industrial waste recycling. The transition to clean energy sources reduces the availability of FGD gypsum in the market.

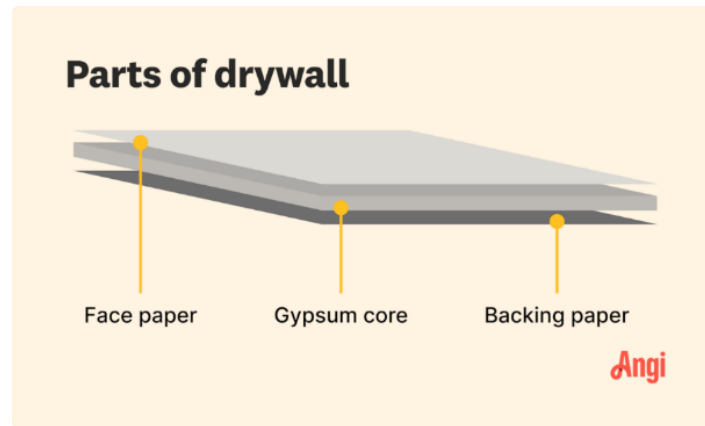
### **II.3.2 Paper Covering (Recycled vs. Virgin Fiber)**

The paper covering for plasterboard, often called "facing paper," plays a crucial role in the board's overall structural integrity and surface finish. The two main types of paper coverings used are derived from either recycled or virgin fibers:

Recycled fiber paper, made from post-consumer or post-industrial waste, serves as plasterboard material because it supports sustainability targets and waste management initiatives. Through its manufacturing method paper production uses less water and chemicals which generates less carbon pollution, and it preserves both water and forests, and its production requires decreased energy consumption. The usage of recycled paper for construction decreases landfill waste deposition while operating as an eco-friendly circular economy supporting building material.

The strength together with smooth surface quality of virgin fiber paper that originates from fresh wood pulp makes it suitable for durable plasterboard needs or applications that require distinctive visual characteristics. Manufacturing virgin fiber paper requires extensive resources which leads to widespread deforestation and damaging habitat destruction and raises the demand for added water and energy use. The Forest Stewardship Council endorses forestry practices focused on sustainability which manage forests through responsible conservation methods to reduce some negative environmental effects.

Plasterboard production can significantly lower its environmental footprint when recycled paper is used as the surface cover material. Compared to virgin paper, recycled alternatives require fewer natural resources and generate less pollution, contributing to reduced energy consumption, water use, and greenhouse gas emissions during manufacturing.



**Figure 2. Parts of Plasterboard**

## **II.4 Mechanical Properties of Plasterboard**

Petrone et al. (2016) conducted an in-depth analysis of mechanical properties as experimentally tested, revealing 302 mechanical tests, for different board types, that evaluated tensile and compressive strength, elastic modulus, board thickness impact and orthotropic behavior.

### **II.4.1 Tensile and Compressive Strength**

The plasterboards displayed examples of different behaviors under tensile and compressive loads. For the tensile loads, the presence of the paper liners had a ductile behavior with yield points and strain before failure, while under compressive loading all the boards failed in a brittle failure with minimal deformation prior to collapse, showing the fragile nature of the gypsum core under compression. The difference in behavior can be seen in Table 2, which shows a comparison of tensile and compressive strengths and elastic moduli for the range of boards and thicknesses.

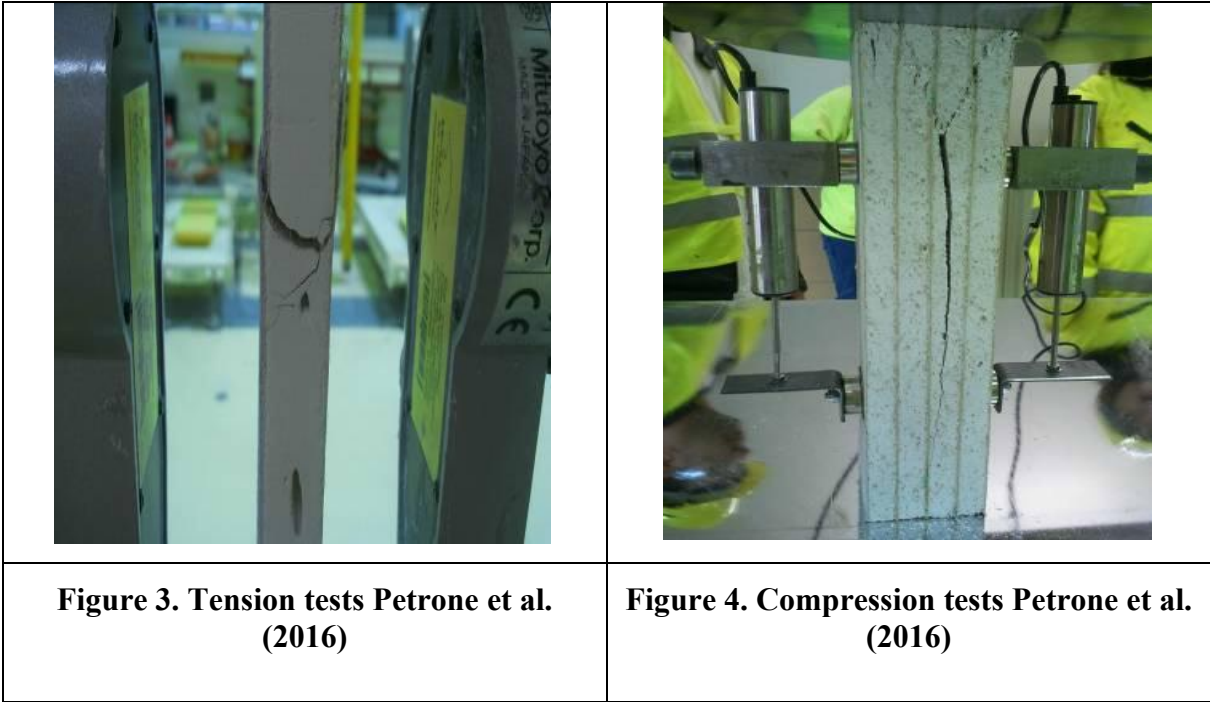
**Table 2. Summary of Mechanical Properties by Board Type**

Board Type	Thickness (mm)	Density (kg/m <sup>3</sup> )	Tensile Strength (MPa)	Compressive Strength (MPa)	Tensile Modulus (MPa)	Compressive Modulus (MPa)
12SB	12.5	720	1.86 (L) / 0.80 (T)	3.27 (L) / 3.02 (T)	1687 (L) / 1362 (T)	2303 (L) / 1779 (T)
18SB	18.0	862	1.55 / 0.68	5.47 / 4.93	4508 / 3300	3608 / 3459
12HDB	12.5	831	2.12 / 1.04	5.86 / 5.10	3736 / 2634	3464 / 3150
15HDB	15.0	893	2.04 / 0.78	7.38 / 5.74	5801 / 4052	3779 / 3609
18HDB	18.0	920	1.44 / 1.15	8.13 / 7.02	4143 / 4228	4539 / 3723

L = Longitudinal, T = Transverse direction

**Note.** Source : Petrone, C., Magliulo, G., & Manfredi, G. (2016).

The data shows that compressive strengths consistently exceed tensile strengths across all configurations. This supports the use of plasterboards in load-bearing or compressive applications but highlights the need for reinforcement in tensile applications.



**II.4.2 Elastic Modulus**

Tension and compression elasticity modules help evaluate stiffness of the plasterboards.

Elastic modulus values are relatively consistent across load types but increase with board density and thickness.

As shown in Table 2, boards of high-density (e.g., 15HDB and 18HDB) have high stiffness, over 4000 MPa in many circumstances even for standard-densities boards. This can be used in structural situations with minimal deformation performance.

**Table 3. Behavior Comparison – Tension vs. Compression**

Property	Tension	Compression
Failure Mode	Ductile (paper liner)	Brittle (core failure)
Directional Dependency	Strong (orthotropic)	Weak
Strength	Lower (0.68–2.12 MPa)	Higher (3.02–8.13 MPa)
Modulus of Elasticity	1362–5801 MPa	1779–4539 MPa
Ultimate Strain	Higher	Lower

**Note.** Source : Petrone, C., Magliulo, G., & Manfredi, G. (2016).

The contrast in material behavior across load types underscores the need to match plasterboard types with their intended mechanical roles in building systems.

#### II.4.3 Thickness Effects

A key finding in Petrone et al's work is the strong correlation between board thickness and mechanical performance. as shown in Table 4. Boards with greater thickness show improved compressive strength and stiffness, likely due to both increased mass and resistance to crack propagation.

**Table 4. Influence of Thickness on Compressive Strength (Longitudinal Direction)**

Thickness (mm)	Standard Density (fc MPa)	High Density (fc MPa)
12.5	3.27	5.86
15.0	—	7.38
18.0	5.47	8.13

**Note.** Source : Petrone, C., Magliulo, G., & Manfredi, G. (2016).

These results suggest that thicker boards, particularly in the high-density category, should be prioritized for installations requiring high load resistance, such as partition walls in high-traffic or fire-rated areas.

#### I.4.4 Orthotropic Behavior

Plasterboards are orthotropic from a mechanical point of view, especially during tensile loading, meaning that the mechanical properties depend on the direction of the applied load in relation to the plaster board's direction of the board's manufacturing. as shown in Table 5, to be more specific, the tensile capacity, including tensile strength and strain, is significantly higher in the longitudinal direction than in the transverse direction, due to the set of the reinforcing paper fibers.

**Table 5. Orthotropic Behavior in Tension**

Board Type	Direction	Tensile Strength (MPa)	Elastic Modulus (MPa)	Ultimate Strain
12SB	Longitudinal	1.86	1687	Higher
12SB	Transverse	0.80	1362	Lower
15HDB	Longitudinal	2.04	5801	Higher
15HDB	Transverse	0.78	4052	Lower

**Note.** Source : Petrone, C., Magliulo, G., & Manfredi, G. (2016).

From these results, installation orientation significantly influences structural performance. For maximum tensile resistance, plasterboards should be aligned longitudinally.

#### II.4.5 Mechanical Performance Summary

The tables provided above lend quantitative evidence to the conclusions proposed by Petrone et al. (2016):

- Compressive strength is greater than tensile strength, which leads to the superior performance of the board in compression.
- The elastic modulus increases with thickness and density, which directly relates to stiffness and deflection behavior.
- Thicker panels demonstrate better mechanical performance, which is significant for applications that experience high loads.
- Orthotropic behavior is important to understand when in tension and a directional understanding is necessary for installation.

Overall, these conclusions form a basis for material selection and structural design in proposals

that involve plasterboard systems to allow for safety and efficiency during construction.

### II.5 Manufacturing Process of Plasterboard

Gypsum rock is produced through natural quarries and transported to the manufacturing plants where it is processed. The entire production process is shown in Figure 5.

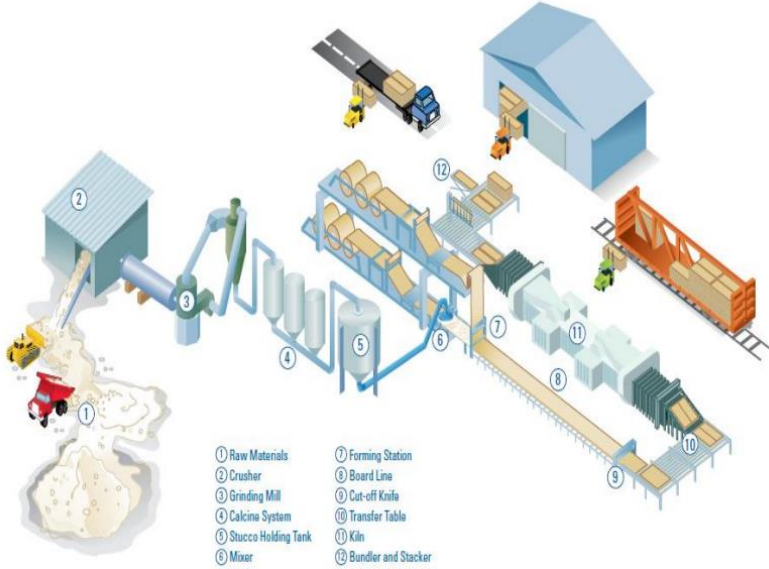


Figure 5. Gypsum Board Manufacturing Process (Georgia Pacific Gypsum, 2010)

#### 5.1 Gypsum Preparation

The manufacturing process of plasterboard begins with mineral gypsum extraction through mining operations of calcium sulfate dihydrate either from source deposits or industrial waste materials in order to decrease the consumption of new materials. The production process begins by processing the gypsum rocks through crushers and mills that reduce them to fine powder. The heating process in large rotating kilns decarbonates gypsum powder and produces stucco which is known as calcium sulfate hemihydrate. This transformation is essential because when water is rehydrated with the resulting stucco, the material hardens to form the solid core of the plasterboard. The manufacturing process utilizes sensors and automated equipment to check the purity as well as consistency of stucco while verifying its proper composition to keep high standards for particle size measurements and moisture content levels.

Modern production uses automated milling systems to achieve fine particle sizes, improving the consistency of plasterboard. Moreover, infrared sensors and real-time chemical analysis tools enhance quality control, allowing adjustments in real time to meet specific standards.

Closed-loop systems that capture and recycle dust contribute to better resource efficiency and reduce airborne particulates.

### **II.5.2 Paper Processing**

Plasterboard paper which forms its exterior component contains recycled materials that provide essential durability around the gypsum core. The paper making starts with pulping and formulation steps to combine recycled materials with other fibers which results in hardened paper for final production. The production process includes treating the paper with polymers and wax emulsions which both provide moisture protection while improving its bond to the gypsum core. The paper quality control process verifies that products have desired characteristics relating to thickness and strength together with moisture resistance standards. The paper completes quality control processes to become rolls which remain stored until needed by the production line to support manufacturing quality consistency.

With increasing emphasis on sustainability, bio-based coatings are being used to replace petroleum-based coatings for moisture resistance. Additionally, digital sensors monitor the paper for consistency in thickness and tensile strength, further ensuring that it meets the required specifications.

### **II.5.3 Slurry and Sandwiching**

Wet plasterboard develops through the method of sandwiching gypsum slurry between two paper sheets. The slurry process requires the addition of water to calcined gypsum to form a pouring substance that coats the prepared paper sheets streaming from conveyor belts. The process of sandwich making starts when a second sheet of paper is placed on top of gypsum slurry. Pressing mechanisms together with rollers maintain equal distribution of slurry between the paper sheets. The wet plasterboard receives dimensional precision from high-precision automated cutting systems that guarantee consistency throughout the final manufactured product.

Today, automated slurry mixers adjust the water-to-gypsum ratio dynamically to achieve optimal consistency. Some plants employ AI-powered quality control systems that monitor the slurry's thickness and uniformity in real-time, ensuring superior adhesion and consistency.

### **II.5.4 Drying and Packaging**

The wet plasterboard passes through a drying chamber which enables moisture removal

to make the board become solid. Through massive drying ovens also known as kilns the boards receive circulation from hot air which removes water content while solidifying the gypsum substance. Post-drying the boards receive final examinations for measurements while the exterior quality and structural integrity is verified. The finished boards receive final packaging for shipment which makes them available for construction sites distribution.

Modern drying kilns use low-energy heating systems that reduce power consumption. Temperature and airflow are controlled by digital sensors, optimizing drying times and energy efficiency. Advanced dryers also use exhaust heat recovery systems to capture and reuse heat, reducing fuel use and emissions.

Table 6. Summary of Manufacturing Process of Plasterboard

Stage	Main Description	Recent Technologies
<b>Gypsum Preparation</b>	Crushing and grinding gypsum into powder, heating it to create "stucco," and ensuring quality.	Automated milling systems, infrared sensors, and real-time chemical analysis for stucco quality and emission reduction.
<b>Paper Preparation</b>	Producing paper from recycled fibers, treating it to improve moisture resistance and quality.	Eco-friendly coatings and digital sensors for monitoring thickness and strength.
<b>Sandwiching Process</b>	Pouring gypsum slurry between two paper layers, pressing, and cutting to required dimensions.	AI-powered mixers for slurry consistency and precision cutting systems to minimize waste.
<b>Drying and Packing</b>	Drying boards in kilns to remove moisture, cooling them, and packaging for shipment.	Energy-efficient dryers, heat recovery systems, and AI-driven inspection for consistent quality.

**II.6 Functional Applications of Plasterboard**

**II.6.1 Residential and Commercial Use**

Plasterboard serves as a fundamental construction material in residential builds because it permits builders to construct partition walls and ceilings through efficient processes that produce neat, finished surfaces (Pedroso et al., 2017). The material's inherent workability and standardized installation procedures allow for the rapid division of rooms within short periods of time, enabling efficient partition creation across residential spaces and various floor plans.

Plasterboard wall construction between bedrooms and bathrooms with living areas builds privacy areas while blocking sound transmission (Hongisto et al., 2022). Plasterboard partitions offer high flexibility because installation experts can easily handle modifications and design changes through cutting and shaping actions. Plasterboard walls in homes make suitable surfaces for painting or wallpaper installation in addition to decorative molding applications (Arroyo et al., 2020).

Plasterboard serves both commercial and industrial buildings by dividing up offices and conference rooms as well as retail sectors and industrial zones (Alkamaly & Albadry, 2025). Plasterboard demonstrates strong adaptability since it works effectively as non-load bearing and fire-resisting walls thus suitable for protection areas which need fire safety and soundproofing measures (Massoudinejad et al., 2019). Office spaces are created through plasterboard partitions that integrate recessed cavities for electrical and communication system access in the partitioned areas (Hopfe & Hall, 2012). Plasterboard finds its primary usage in industrial spaces to construct smooth walls which achieve fire safety standards particularly in areas with elevated fire risk (Klemczak et al., 2024). The manufacturing industry provides specialized fire-resistant boards among the various types of plasterboard available for specific purposes (Karataş et al., 2025).

As shown in Table 7, the comparative analysis highlights differences in plasterboard use across residential and commercial environments, emphasizing how adaptability, safety, and finish quality vary depending on the functional context of construction.

**Table 7. Comparison of Residential and Commercial Plasterboard Applications**

<b>Aspect</b>	<b>Residential Use</b>	<b>Commercial/Industrial Use</b>
<b>Primary Function</b>	Used for partition walls and ceilings to create private and aesthetic spaces.	Used for office partitions, fire-resistant and soundproof walls.
<b>Flexibility and Adaptability</b>	Easily cut and reshaped for design modifications in interior structures.	Allows incorporation of wiring and service cavities in walls.
<b>Safety &amp; Durability</b>	Offers sound insulation between rooms for privacy.	Fire-resisting boards enhance safety in industrial zones.
<b>Finish Quality</b>	Smooth, paint-ready, and supports decorative finishes.	Enables smooth, durable walls meeting industrial standards.

**Note.** Sources : Pedroso et al. (2017); Alkamaly & Albadry (2025); Arroyo et al. (2020); Hopfe & Hall (2012); Hongisto et al. (2022); Karataş et al. (2025); Klemczak et al. (2024); Massoudinejad et al. (2019).

This table highlights differences in plasterboard applications across residential and commercial contexts—commercial usage emphasizes safety and performance, while residential settings focus on flexibility and finish quality.

### II.6.2 Acoustic Insulation

Plasterboard demonstrates strong sound reduction properties which convert it into an optimum choice for both residential and commercial applications requiring noise control (Korjakins et al., 2025). The partition walls made from plasterboard in residential homes perform the crucial task of maintaining sound isolation between bedroom spaces together with bathroom and living quarters (Mohammed & Meincken, 2023). Plasterboard functions as a tool for office and conference room confidentiality by blocking external noises in commercial settings (Al-Homoud, 2005). Plasterboard obtains increased acoustic performance when soundproofing materials such as mineral wool and foam and specialized acoustic plasterboard with denser cores are used for blocking sound transmission (Fediuk et al., 2021). The additional materials improve the sound absorption properties of the board to establish it as a preferred acoustic solution (Asdrubali et al., 2012).

As illustrated in Table 8, the acoustic and thermal insulation roles of plasterboard share overlapping benefits yet differ in their material composition and efficiency mechanisms.

**Table 8. Acoustic and Thermal Insulation Performance of Plasterboard**

<b>Parameter</b>	<b>Acoustic Insulation</b>	<b>Thermal Insulation</b>
<b>Core Function</b>	Reduces sound transmission between spaces using dense or layered boards.	Minimizes heat transfer, improving energy efficiency and comfort.
<b>Enhancing Materials</b>	Mineral wool, foam, acoustic plasterboards with denser cores.	Fiberglass panels, rigid foam, or eco-based insulating composites.
<b>Efficiency Impact</b>	Increases privacy and reduces workplace noise levels.	Reduces heating and cooling costs by stabilizing indoor temperature.
<b>Sustainability Aspect</b>	Can incorporate recycled acoustic materials.	Often integrated with low-emission, recyclable thermal materials.

**Note.** Sources : Hongisto et al. (2022); Kośny & Yarbrough (2022); Fediuk et al. (2021); Balador et al. (2018); Asdrubali et al. (2012); Teesdale (1958); Neri (2022); Salih (2016).

Both insulation types enhance comfort and sustainability—acoustic applications improve sound control, while thermal boards boost energy conservation.

### **II.6.3 Thermal Insulation**

The thermal insulation function of plasterboard consists of protecting indoor temperatures through its protective barrier against heat loss or gain (Kośny & Yarbrough, 2022). Plasterboard installations within cooler climates diminish room energy loss thus leading to better energy efficiency and increased comfort levels in living or working areas (Teesdale, 1958). The consistent indoor temperature reaches maintained levels by plasterboard which decreases the need to operate heating and cooling systems thus saving energy expenses (Salih, 2016). Plasterboard functions as an insulation material but homeowners can enhance performance through partnership with high-quality materials such as rigid foam and fiberglass panels to achieve maximum thermal advantages in energy-efficient spaces (Balador et al., 2018). These wall and ceiling systems prove most effective in building structures because they enhance energy conservation properties while promoting environmental friendliness (Neri, 2022).

### **II.6.4 Ceiling Construction**

Plasterboard serves both commercial and residential construction through its use as suspended ceilings together with directly fixed ceilings (Robert et al., 2025). Commercial and industrial buildings frequently use suspended ceilings constructed as a grid system beneath main ceilings that receive plasterboard panels within its framework (Korjajkins et al., 2025). Plasterboard provides convenience for utility access while improving noise reduction and allows simple easy access to the space (Hongisto et al., 2022). Plasterboard ceilings work best for large buildings such as offices and shopping malls, and they enable builders to incorporate built-in lighting and ventilation systems (Al-Homoud, 2005). The residential use of residential buildings relies on directly fixed ceilings when plasterboard connects directly to structural ceiling beams (Karataş et al., 2025). These ceilings enable smooth surfaces which a skilled installer can transform into different configurations that span from curved to coffered designs thus giving architects multiple aesthetic options (Pedroso et al., 2017). Construction companies enhance these ceilings by incorporating built-in insulation or acoustic panels to provide superior thermal and soundproofing benefits (Ouda et al., 2025).

As displayed in Table 9, ceiling applications of plasterboard differ mainly in installation technique and environmental performance between residential and commercial structures.

**Table 9. Comparison of Ceiling Construction Types Using Plasterboard**

<b>Type of Ceiling</b>	<b>Suspended (Commercial)</b>	<b>Directly Fixed (Residential)</b>
<b>Installation Method</b>	Grid system below structural ceiling; easy utility access.	Attached directly to ceiling beams; smooth finish.
<b>Functional Benefits</b>	Enhances sound absorption, allows for integrated lighting and HVAC systems.	Enables curved or coffered designs, improving aesthetics.
<b>Thermal &amp; Acoustic Role</b>	Supports fire-resistant and sound-absorbing panels for large buildings.	Incorporates insulation layers for comfort and quietness.
<b>Application Settings</b>	Offices, malls, and industrial spaces.	Homes, apartments, and small residential buildings.

**Note.** Sources : Korjakins et al., 2025; Robert et al. (2025); Hongisto et al. (2022); Karataş et al. (2025); Al-Homoud (2005); Ouda et al. (2025); Arroyo et al. (2020); Teesdale (1958). This table compares ceiling systems used in different building contexts—suspended ceilings prioritize service access, while direct-fix ceilings focus on design quality and comfort.

HVAC: stands for Heating, Ventilation, and Air Conditioning.

**Table 10. Integrated Comparison of Functional Benefits**

Feature	Residential	Commercial	Acoustic	Thermal	Ceiling Systems
<b>Main Objective</b>	Aesthetics and comfort	Safety and efficiency	Noise reduction	Energy efficiency	Aesthetic + functional integration
<b>Material Enhancements</b>	Paint, wallpaper	Fire-resistant cores	Mineral wool, foam	Rigid foam, fiberglass	Composite plasterboard
<b>Environmental Impact</b>	Moderate	Moderate	Sustainable options available	High eco-benefit	Depends on configuration
<b>Performance Longevity</b>	High (interior use)	Very high (industrial standards)	Moderate-high (material dependent)	High (energy-saving)	High (durable and replaceable)

**Note.** Sources : Pedroso et al. (2017); Alkamaly & Albadry (2025); Hongisto et al. (2022); Kośny & Yarbrough (2022); Robert et al. (2025); Al-Homoud (2005); Fediuk et al. (2021).

This integrated comparison summarizes plasterboard's multifunctionality across building types, balancing sustainability, aesthetics, and performance.

## II.7 Fire Resistance and Safety in Gypsum-Based Wall Systems

### II.7.1 Scientific Basis of Fire Resistance

Gypsum plasterboards are widely recognized for their role in passive fire protection. The key to the performance of gypsum fire resisting plasterboards is in the dehydration of calcium sulfate dihydrate ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ), of which is approximately 21% water by weight. This bound water regularly evaporates in an endothermic reaction when subjected to heat, delaying the temperature rise significantly on the unexposed side (Kang, 2023). Board types can be classified mainly into Type A (standard) and Type F (fire-rated), as shown in Table 11

**Table 11. Comparison of Gypsum Board Types**

Property	Type A (Standard)	Type F (Fire-rated)
Reinforcement	None	Glass fiber
Typical Thickness (mm)	12.5	15
Water Content (%)	21	21
Max Effective Temp (°C)	Up to 300	Up to ~700°C

**Note.** All data extracted from Just et al. (2010). Glass-fiber reinforcement delays fall-off at elevated temperatures.

Type F's enhanced fire performance is attributed to the inclusion of glass fiber reinforcement which holds the board together at a temperature often above ~700°C (Just et al., 2010). However, performance in the real world will be impacted not only by board construction but also by system-level factors such as:

- Number of layers
- Type of fasteners and their spacing
- Edge treatment and the sealing of joints
- The use of insulation in cavities

These key design factors are summarized below.

**Table 12. Key Factors Affecting Fire Resistance**

Factor	Impact on Fire Resistance
Board Thickness	Thicker boards delay heat transfer
Number of Layers	More layers improve protection
Insulation Type	Dense mineral wool improves insulation
Joint Treatment	Staggered, sealed joints prevent flame spread
Fastener Spacing	Closer spacing increases mechanical hold

**Note.** Information adapted from Just et al. (2010) fire performance database.

## II.7.2 Case Studies and Empirical Evaluations

### CSIRO Penetration Test (Australia, 2020)

Four penetration methods (including Rehau pipes and steel beams) were examined by a CSIRO study using a Knauf FireShield plasterboard assembly on both sides of a 92 mm steel stud frame with mineral wool insulation. All breaches to the building envelope were sealed by using FireMastic-HPE fire-rated sealants. The system could maintain its insulation and structural properties for a full 60 minutes without being loaded up to minimum requirements (CSIRO, 2020). That reveals why designing the whole system with plasterboard, sealants and frame is necessary for sufficient performance. But, focusing on particular penetrations means the study can't be used for all configurations which means new tests are needed.

### **SP Trätek Study (Europe, 2010)**

Just et al. (2010) tested the fire performance of 340 timber-frame structures covered with gypsum plasterboard, resulting in new equations for estimating the building's resistance to failure in case of fire. According to the testing, a failure happened when 1% of the board area came detached—this was affected by the choice of board, fastener type and cavity insulation. Glass fiber-reinforced Type F boards worked better than standard Type A boards which normally resist burning for more than 40 minutes in furnace testing. The research resulted in generating equations for:

- Charring time (tch), refers to the moment wood reaches 300°C
- The failure time (tf) is determined by studies of fastener pull-out strength and board material condition.

The EN 1995-1-2 design guidelines now benefit from the safety improvements suggested by these equations. Even so, the timber approach of the study does not cover all cases, so further study should bridge this gap (Just et al., 2010).

### **GIB® Testing Approach (New Zealand, 2023)**

GIB® employs rigorous fire testing using AS 1530.4:2014 protocols. Failure modes are assessed based on:

- Structural adequacy
- Integrity
- Insulation performance

GIB® systems demonstrate consistent resistance for **30–90 minutes**, and the integration of thermocouples during testing provides valuable insights into cavity dynamics under fire

exposure.

The findings from all these case studies are summarized below.

**Table 13. Summary of Fire Test Results**

Case Study / Source	System Construction	Standard Used	Failure Characteristics	Mode	Fire-Resistance Outcome
<b>CSIRO (2020)</b>	Knauf FireShield 13 mm + steel studs + 75 mm mineral wool	AS 1530.4	Integrity and insulation maintained for required duration		Classified -/60/60 under full-scale testing
<b>Just et al. (2010)</b>	Type A vs. Type F plasterboard cladding on timber frames	EN 1995-1-2 database	Type A loses cohesion early; Type F delays fall-off due to glass fibers		Improved performance for Type F systems under fire exposure
<b>GIB® (2023)</b>	GIB® fire-rated assemblies using cavity insulation + joint protection	AS 1530.4	Fire performance governed by complete system design		Full-scale testing confirms system-level fire resistance

### II.7.3 Conclusion

Research demonstrates that the performance of gypsum boards is governed by both material chemistry and the system-level assembly. While Type F boards provide higher thermal resistance, performance also relies on proper spacing of fasteners, use of dense insulation, and joint treatments.

Further advancements in fire-resistant system design should focus on:

- Transparency in manufacturer testing data
- Compatibility with non-proprietary building components
- Sustainable use of recycled/industrial gypsum
- Adoption of EN-based conservative equations for safety design

## II.8 Soundproofing Characteristics of Plasterboard

### II.8.1 Sound Absorption Mechanisms

Plasterboard systems (often comprised of gypsum) are widely utilized for sound insulation, particularly in modern building applications, due to their mass-law performance characteristics, versatility in layering, and suitable conformability to complex acoustic systems. The key properties behind this type of acoustic performance rely on mass, decoupling through airspace gaps, and porous absorption provided by internal insulation.

Uris et al. (2006) investigated a double-frame plasterboard partition with mineral wool (DF2+1) which achieved sound transmission class (STC) ratings within Canada of 57 dB, especially between 100-200 Hz. When control of low frequencies is a concern, additional thickness (layering) does not always lead to the best performance due to resonance. A similar concern was demonstrated by Cuce et al. (2019), who noted thicker and denser gypsum cores, which reduced the barrier effect of external noise due to vehicular traffic as an example. Pedreño-Rojas et al. (2020) took a similar research stance by finding that densified recycled gypsum systems improved sound insulation within an urban apartment conceptualization.

Both Smith (2004) and Way & Couchman (2008), echoed the need to couple plasterboard with mineral wool or fibreglass for low to mid-frequency (and broadband) absorption within lightweight construction.

These findings are supported by the comparative data presented in Table 14.

**Table 14. STC and Acoustic Performance Comparison of Common Materials**

<b>Materials</b>	<b>STC Rating</b>	<b>Low-Frequency Isolation</b>	<b>High-Frequency Absorption</b>	<b>Echo Control</b>
<b>Plasterboard + Mineral Wool (Double Frame)</b>	57	Moderate	Good	Good
<b>Concrete Wall (200 mm)</b>	53–54	High	Poor	Poor
<b>Acoustic Panels (polyester or foam)</b>	30–35	Low	Excellent	Excellent
<b>Fiberglass Insulation (in cavity)</b>	45–50	Moderate	Excellent	Good
<b>Mineral Wool (in cavity)</b>	47–48	Moderate	Excellent	Good

**Note.** All values derived from scientific and engineering studies: Uris et al. (2006), Salih (2016), Smith (2004), Yu (2015), Way & Couchman (2008), and Henke (2022).

II.8.2 Applications of Plasterboard in Architectural Acoustics

Plasterboard serves a significant purpose in areas where acoustics and clarity-in-speech are particularly important, such as studios, theatres, offices, schools, and multi-dwelling residential units.

Henke (2022) indicates that in professional recording studios, walls built from double framed gypsum board and mineral wool insulation, will typically exceed STC 55, isolating the recording space and control room. Following a similar principle, Uris et al. (2006) evaluated a movie theater that utilized a plasterboard and absorptive core (DF(2+1)), which allowed them to limit sound transmission by achieving a remarkable transmission loss of over 57 dB, thereby insulating the decorated space from the outside environment.

As summarized in Table 15, in single-family homes and mixed-use high-rises, recycled, high density gypsum panels provide the best compromise of sustainability and audio performance across walls and ceilings (Pedreño-Rojas et al., 2020). Office spaces benefit as well with a similar gypsum partition wall and acoustic baffling tiles as shown by Tabassum (2021) achieving optimal performance and more productivity by addressing reductions in speech distraction.

Table 15. Acoustic Applications of Plasterboard Systems

Application Context	Typical System Configuration	Acoustic Objective
Recording Studios	Double gypsum + mineral wool + air gap	Isolation & sound clarity
Cinemas	Double frame + 2 layers + mineral wool	Sound containment
Apartments	Recycled gypsum + dense wall insulation	Urban noise reduction
Open-plan Offices	Gypsum partitions + baffles + ceiling tiles	Speech intelligibility
Schools / Classrooms	Gypsum board + acoustic ceilings	Reverberation control

Note. Acoustic application data sourced from Henke (2022), Uris et al. (2006), Pedreño-Rojas et al. (2020), Tabassum (2021), and Yu (2015).

II.8.3 Comparative Analysis: Plasterboard vs. Competing Materials

When compared to traditional building materials like concrete, fiberglass, acoustic panels, and mineral wool, it can be determined that plasterboard is an adaptable, multi-

functional option that achieves an adequate balance of mass for sound blockage and an absorptive core for sound dissipation.

Concrete has a high mass and is effective in isolating sound at low frequencies, however, its reflective properties create undesirable echo (Salih, 2016). Acoustic panels are efficient at absorbing sound internally but do little to provide transmission loss. Fiberglass and mineral wool are very low mass materials, but effective cavity absorbers when placed in a layered wall assembly.

This comparative analysis is detailed in Table 16.

**Table 16. Comparative Acoustic and Practical Properties of Building Materials**

<b>Feature / Material</b>	<b>Plasterboard + Mineral Wool</b>	<b>Concrete (200 mm)</b>	<b>Acoustic Panels</b>	<b>Fiberglass (in cavity)</b>
<b>Acoustic Function</b>	Balanced solution combining mass and cavity absorption	Heavy mass barrier	Surface absorber	Porous absorber in lightweight walls
<b>Low-Frequency Isolation</b>	Moderate	High	Low	Moderate
<b>High-Frequency Absorption</b>	Good	Poor	Excellent	Excellent
<b>Echo Control</b>	Good	Poor	Excellent	Good
<b>Material Mass</b>	Medium	High	Low	Low
<b>Installation Complexity</b>	Medium	High	Low	Low
<b>Recyclability</b>	High	Low	High	Moderate

**Note.** Comparative material properties compiled from Uris et al. (2006), Salih (2016), Smith (2004), Yu (2015), Way & Couchman (2008), Henke (2022), and Pedreño-Rojas et al. (2020).

#### **II.8.4 Sustainability and Future Research Directions**

Recent developments have examined the application of recycled gypsum, eco-binders, and plant-based acoustic cores (Woolley, 2022) to promote sustainability while maintaining performance; however, recycled materials can vary, which can create inconsistencies regarding acoustics.

Future research should be examined:

- Flanking transmission in more complex geometries
- Tolerances in on-site installations
- Hybrid acoustic-thermal systems for green buildings
- Creation of simulation tools (e.g., ODEON, INSUL) to validate predictions of real-world STL in partition walls

## **Conclusion**

Across all reviewed studies, plasterboard, particularly in double-frame configurations with mineral or fiberglass wool—demonstrates consistent effectiveness for both airborne noise isolation and internal acoustic comfort. While materials like concrete and acoustic panels serve more specialized roles, plasterboard offers a cost-effective, versatile, and scalable solution that supports modern architectural and sustainability goals.

**II.9 Chapter Conclusion**

Chapter II defines plasterboard as groundbreaking material in modern construction and outlines how it has become a performance-based material capable of justifying its existence as anything other than a labor-saving material. The analysis shows that the high-functional qualities of the material, namely, acoustic insulation, thermal regulation, and passive fire protection are not necessarily intrinsic to the gypsum core but are deeply dependent on the design of the system. Specifically, mechanical resilience is based on such factors as thickness, density, and orthotropic alignment, whereas the multi-layered assemblies, proper joint sealing, and the use of ancillary materials like mineral wool are the variables that affect fire resistance and acoustic performance primarily.

Besides, the contemporary production process reflects a growing concern in the field of sustainability, which is reflected by the use of synthetic gypsum and recycled paper fibers, but, at the same time, the incorporation of special additives aimed at performance increase also creates difficulties in the end-of-life recycling. This chapter provides the necessary technical and environmental parameters by providing a comprehensive technical review of the history, composition, properties and application of plasterboard. This overall lifecycle knowledge has now become the fundamental basis to the subsequent exploration of the major issues and innovative solutions towards the sustainable disposal and the positive reuse of plasterboard waste, which shall form the subject matter of further chapters.

## Chapter III. Climate changes caused by the accumulation of Waste

### III.1 Waste Accumulation and Its Role in Global Climate Change

The improper disposal of waste by humans creates major global climate change problems. The decomposition of organic waste in landfills produces methane (CH<sub>4</sub>) through anaerobic processes which functions as a greenhouse gas that has 25 times the warming potential of carbon dioxide (CO<sub>2</sub>) during a 100-year period according to the IPCC (2014). The open waste burning process produces methane as well as dioxins and furans and other dangerous substances which strengthen the greenhouse effect and make air quality worse.

#### III.1.1 Greenhouse Gas Emission Pathways from Waste

Multiple waste categories contribute to GHG emissions through distinct mechanisms. These are summarized in Table 17 below:

**Table 18. Waste Categories and Their Greenhouse Gas Contributions**

Waste Category	Decomposition Process	GHG Emissions	Additional Notes
<b>Organic Waste</b>	Anaerobic landfill decomposition	Methane (CH <sub>4</sub> )	Responsible for ~10% of global methane emissions IPCC (2019)
<b>Plastic Waste</b>	Incineration, photodegradation	CO <sub>2</sub> , CH <sub>4</sub> , dioxins	Releases microplastics and POPs
<b>E-Waste</b>	Burning, informal recycling	Heavy metals, brominated compounds	High toxicity risk
<b>Construction Waste</b>	Landfill disposal, open dumping	CO <sub>2</sub> , CH <sub>4</sub>	Often unrecycled; inefficient use
<b>Paper/Cardboard</b>	Decomposition, combustion	CH <sub>4</sub> , CO <sub>2</sub>	Biodegradable, yet GHG-intensive in landfills
<b>Metal Waste</b>	Mining, smelting	CO <sub>2</sub>	High carbon footprint in extraction and processing

**Note.** Data compiled from: Gautam & Agrawal (2020); Gouda et al. (2025); Fawole et al. (2023); Goh et al. (2022); Hong et al. (2015); Ramteke et al. (2025); Farag et al. (2025); Intergovernmental Panel on Climate Change [IPCC] (2014, 2019).

### III.1.2 Case Study: The Ghazipur Landfill, India

The Ghazipur landfill, located in East Delhi, reaches a height of more than 65 meters making it one of India's largest waste mounds (Frayar, L. NPR, 2019). As shown in the figure 6 and produces high amounts of methane and volatile organic compounds (VOCs).



**Figure 6.** The towering Ghazipur Landfill emitting smoke and methane in Delhi, India. *Shala, A. (2025)*

This is seen to have ignition events which occur more frequently due to the presence of gas and in addition to this leads to unhealthy smog which is typical of Delhi. It exposes populations living nearby to respiratory risks which can be attributed to the continuous pollution of the air which is given off by the toxic landfills.

**Table 19. Analytical Overview – Ghazipur Landfill Case Study**

Case Study	Environmental Issues	Key Results	Limitations	Policy Implications
<b>Ghazipur Landfill (India)</b>	Methane emissions, toxic gas release, air pollution	Frequent fires; high VOC concentration; smog intensification	No gas capture system; poor segregation; overcapacity	Landfill gas recovery systems, waste sorting, and community health programs

## III.2 Overexploitation of Raw Materials and Environmental Consequences

Excessive exploitation of raw materials has severe ecological effects. The dependence of the global economy on mining, logging, and industrial agriculture has created the unsustainable wear and tear of the key raw materials. This excessive use hastens environmental degradation, which is expressed in deforestation, loss of biodiversity, greenhouse gas (GHG) emissions and loss of soil. (Rockström et al., 2009; Steffen et al., 2015).

table below summarizing the key ideas from the two foundational sources:

**Table 20. Summary of Key Findings on Ecological Limits**

<b>Author(s)</b>	<b>Main Focus</b>	<b>Key Findings</b>	<b>Relevance to Raw Material Exploitation</b>
<b>Rockström et al. 2009</b>	Introduced the concept of “planetary boundaries” that define the safe limits of human activity on Earth’s systems.	Identified nine critical planetary boundaries (e.g., climate change, biodiversity loss, land-system change). Warned that exceeding these limits could cause irreversible environmental damage.	It shows how human extraction and use of raw materials push the Earth beyond its ecological limits, especially in land use and resource depletion.
<b>Steffen et al. 2015</b>	Updated and expanded the planetary boundaries framework with improved data.	Found that four boundaries (climate change, biosphere integrity, land-system change, biogeochemical flows) have already been exceeded due to human activities.	Reinforces the link between overexploitation of resources (e.g., mining, agriculture, deforestation) and global ecological instability.

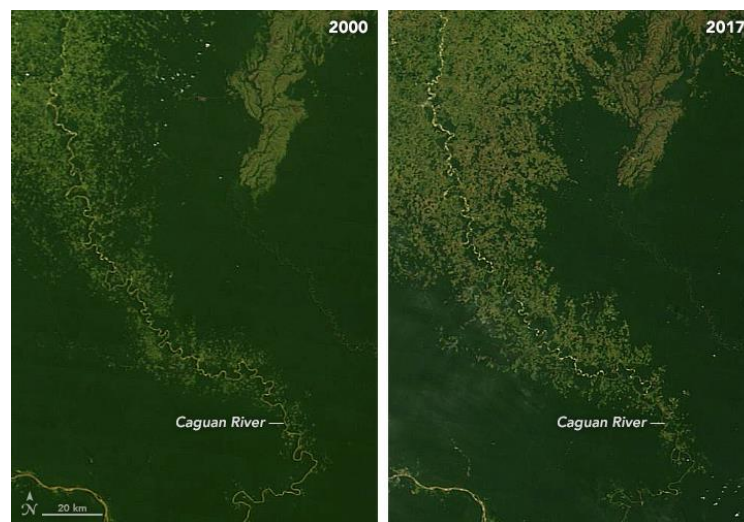
### III.2.1 Overconsumption Cycle

The recent trends of consumption have increased the need of rare earth minerals, timber and arable land. Mining infrastructure- mining activities, especially open-pit mining and

mountaintop removal, result in a large amount of waste, water stress, and landscape alteration (Sonter et al., 2018; Ali, 2014). Timber logging and forest conversion to agriculture also have a direct impact on forest loss, which in turn reduces the capacity to sequester carbon and increases the levels of GHG emissions (Curtis et al., 2018; FAO & UNEP, 2020; IPCC, 2019).

### III.2.2 Case Study: Amazon Rainforest.

The Amazon rainforest exemplifies the severe environmental consequences of excessive raw material use and deforestation. Large-scale logging and agricultural expansion, particularly for soy cultivation and cattle ranching, drive annual deforestation of approximately 6,475 km<sup>2</sup> INPE (Instituto Nacional de Pesquisas Espaciais) (2024), leading to extensive soil erosion and climate disruption. . Figure 7 provides a visual representation of these deforestation patterns in Amazon.



**Figure 7. Satellite image showing deforestation patterns in the Amazon. (Voiland, A. (2019))**

The removal of tree cover destabilizes soil, depleting its fertility and hindering natural nutrient cycles, making land restoration difficult. Additionally, deforestation weakens the Amazon's role as a vital carbon sink, reducing its capacity to absorb atmospheric CO<sub>2</sub> and exacerbating global warming. The carbon released from cleared trees further accelerates climate change, underscoring the importance of conservation policies to mitigate these impacts

**Table 21. Analytical Overview – Amazon Rainforest Case Study**

Case Study	Environmental Issues	Key Results	Limitations	Policy Implications
<b>Amazon Rainforest</b>	Deforestation, carbon sink loss, biodiversity threats	Soil erosion; CO <sub>2</sub> increase; climate feedback loops	Weak enforcement; illegal logging; rising agricultural demand	Strengthening deforestation controls; incentivizing conservation; sustainable land use

**III.3 Impacts of Gypsum Board Waste**

**III.3.1. Hydrogen Sulfide Emissions**

A waste product of gypsum boards produced as a by-product of the demolition works or production processes is a danger to the environment. They are mainly made of calcium sulfate dihydrate and can disintegrate to produce hydrogen sulfide (H<sub>2</sub>S) under anaerobic, damp conditions. The gas that is formed has a characteristic rotten-egg odor and it may be fatal when in high concentrations. When gypsum waste is disposed of in landfills, around 25% of its weight can transform into hydrogen sulfide, especially when mixed with biodegradable materials. Because of this risk, the United States has been evaluating policies to restrict or ban the partial or complete disposal of gypsum board waste in landfills containing organic waste. Similarly, the European Union (EU) has implemented strict regulations to limit the amount of gypsum waste allowed in landfills, including a prohibition on dumping such waste in non-specialized sites. As a result, gypsum board residues must be deposited only in designated, controlled landfills (Gypsum Recycling International, 2014).

Note: Gypsum Recycling International A/S (GRI) is a Danish business that was founded in 2001, and which has led the way in the closed-loop recycling of plasterboard and gypsum wastes. It gathers, recycles, and recycles gypsum based on the construction and destruction sites into the manufacture of new plasterboard. The system significantly decreases landfills and environmental implications that come with garbage disposal of gypsum such as the emission of hydrogen sulfide. GRI model has been implemented successfully in various European nations and is seen as one of the best models of what circular-economy entails in the construction sector.

**III.3.2. Land Use Plan**

Discarded gypsum plasterboards from production facilities occupy a considerable

amount of storage space within the plant. Because of their chemical composition, these waste boards require special storage conditions — they must be kept in dry, well-protected areas, away from rain and high humidity, to avoid the generation of hydrogen sulfide gas (H<sub>2</sub>S) as previously discussed (Gypsum Recycling International, 2014).



**Figure 8. Waste Gypsum Board consuming a Large Area of the Plant (Bunzel, J.-M. (2024))**

### III.3.3. Depletion of Natural Resources

The exhaustion of natural resources has become a worldwide concern, leading people everywhere to seek ways to use these materials more responsibly and efficiently. In this regard, gypsum board waste should not be considered useless, but rather a material that can serve as a raw input or by-product in other industries. Building a sustainable gypsum industry means evaluating the product throughout its entire life cycle.

Gypsum is a mineral product that is naturally found with calcium sulfate dihydrate (CaSO<sub>4</sub> + 2H<sub>2</sub>O). Even though significant reserves are available in quarries around the globe, the issue about its sustainability is growing in the future as the world demand is increasing (Gypsum Recycling International, 2014).

Synthetic gypsum, also known as flue gas desulfurization (FGD) gypsum, is not obtained from mining. Instead, it is produced using limestone and lime—both of which are natural materials—so their consumption should also be minimized to protect natural resources.

### III.3.4. Increasing the Use of Landfills

Disposing of gypsum board waste in landfills has two major drawbacks. The first is that it can lead to the generation of toxic hydrogen sulfide gas, which means such waste must be placed in specially controlled landfills, as previously noted. The second issue is the limited availability of landfill space, which is insufficient to accommodate the hundreds of thousands of tons of gypsum waste produced. With the rising volume of waste disposal, many landfills are reaching capacity at an alarming rate (Environment Agency, 2010).



**Figure 9. Disposal of Waste Gypsum Boards in Landfills (BuildingGreen, Inc. (2012))**

Landfills are an old practice in waste management which was traditionally used as an alternative approach to unregulated open dumping and burning. Since a few decades ago, the government agencies started the development of landfills to dispose of the municipal waste under the systematically regulated conditions, which prevents the waste accumulation uncontrollably in the vicinity of the urban centers. In these plants, the material is compacted and later covered daily with soil, dust, or foam, which are used to protect the refuse against precipitation and wind, and to prevent the intrusion of insects and birds.

Modern landfills are designed and constructed following high standards. In order to prevent the excess of leachate to soils, baselines should include liners made of plastic, clay, or any other

impermeable material to prevent the escape of leachate, the liquid formed in the process of decomposition of waste. The drainage network of pipes will have to be provided as well to receive and channel the leachate into treatment programs. Monitoring of ground water will be an obligatory condition even after the closure, so that the contaminants will not penetrate the underground water sources.

Aerobic degradation of organic waste produces methane (CH<sub>4</sub>), which is a vital risk. Despite its non-toxicity, methane is highly flammable, hence pre-disposing the substance to explosive reactions with oxidizing agents. Methane can also penetrate the nearby buildings, which are safety hazards to the occupants. As a result, some of the buildings that are located near the landfill sites are fitted with methane recovery systems that are installed under basements hence trapping the gas and reducing its effects.

To deal with such issues, the U.S. Environmental Protection Agency (EPA) has issued stringent policies that would require proper designing and managing landfills to reduce risks linked to leachate leakage and emission of methane gases. All licensed operators of landfills are bound to comply with these regulations.

Although landfill operation is so controlled, it has significant environmental disadvantages. Poorly maintained sites may develop into highly polluted places and even properly built facilities will be consuming huge areas of land that could have served other constructive purposes. Landfills also cause the pollution of soil and groundwater, the attraction of vectors (insects and pests), and the increase in global warming due to methane emissions. The most important is the fact that waste burial leads to irreversible destruction of useful material that can be recovered or recycled.

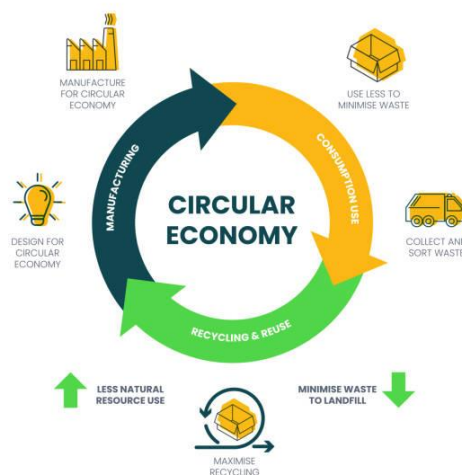
It is therefore urgent that the use of landfills should be reduced and recycling of waste materials like gypsum boards should be encouraged. Increasing recycling levels would reduce the quantities of virgin gypsum that have to be mined, which would save the natural resources and result in a smaller environmental footprint of the waste management process.

### III.4 Conclusion

The build-up of municipal solid waste and insufficient treatment are major contributors to global climate change; this is mainly done by the release of large amounts of greenhouse gases methane (CH<sub>4</sub>) and carbon dioxide (CO<sub>2</sub>) emission. Case studies, such as the one done in Ghazipur landfill in India, and empirical evidence reveal that inadequate waste management triggers critical air pollution and other health threats to the population.

At the same time, excessive use of raw materials and massive deforestation such as those occurring in the Amazon rainforest drive the planet past its ecological boundaries reducing biodiversity and carbon sequestration potential. The disposal of gypsum boards also depicts the contribution of the industrial by-products to the toxicity emissions and waste of resources which is not necessary.

The mitigation involves minimization of landfill reliance, encouragement of recycling efforts, and implementation of circular economy measures. Sustainable management of waste and resources is required to reduce greenhouse gas emission, maintain the natural resources and reduce the rate at which climate change occurs.



**Figure 10. Circular economy model diagram showing waste reduction, reuse, and recycling loops.**

## Chapter IV. Impact of Plasterboard on the Environment

### IV.1 Environmental Challenges of Plasterboard Waste

Plasterboard, mainly composed of gypsum (calcium sulfate dihydrate), and which is coated in paper, is widely used in construction (Figure 8). However, it is a material that is generally considered to have a major environmental problem if not managed properly. In landfills, gypsum can break down in an anaerobic environment and release hydrogen sulfide ( $H_2S$ ), which is both toxic and carries an odour that can affect breathing. The presence of paper can intensify biological activity and increase the release of hydrogen sulfide gas and further contamination of the environment. In addition, plasterboard is low-density material that takes up a lot of space which can contribute to decrease landfill space and accelerate the rapid filling of the landfill. The following will explore the problems in detail.



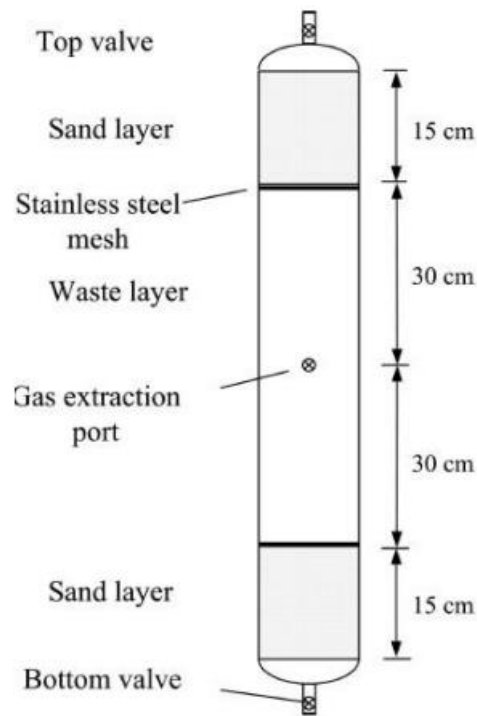
**Figure 11. A pile of plasterboard waste in a landfill.**

#### IV.1.1 Landfill Gas Emissions: Hydrogen Sulfide ( $H_2S$ )

Dumping gypsum board waste in landfills is of great concern due to the huge amount of Hydrogen Sulfide Gas ( $H_2S$ ) generated. When gypsum boards are exposed to moisture in the presence of sulfate reducing bacteria, is produced. This emitted gas has a very bad odor (reminiscent of that given off by rotting eggs) when found in low concentrations. Gas is a source of considerable annoyance to communities in the vicinity of the landfill. (Yang et al, 2006)

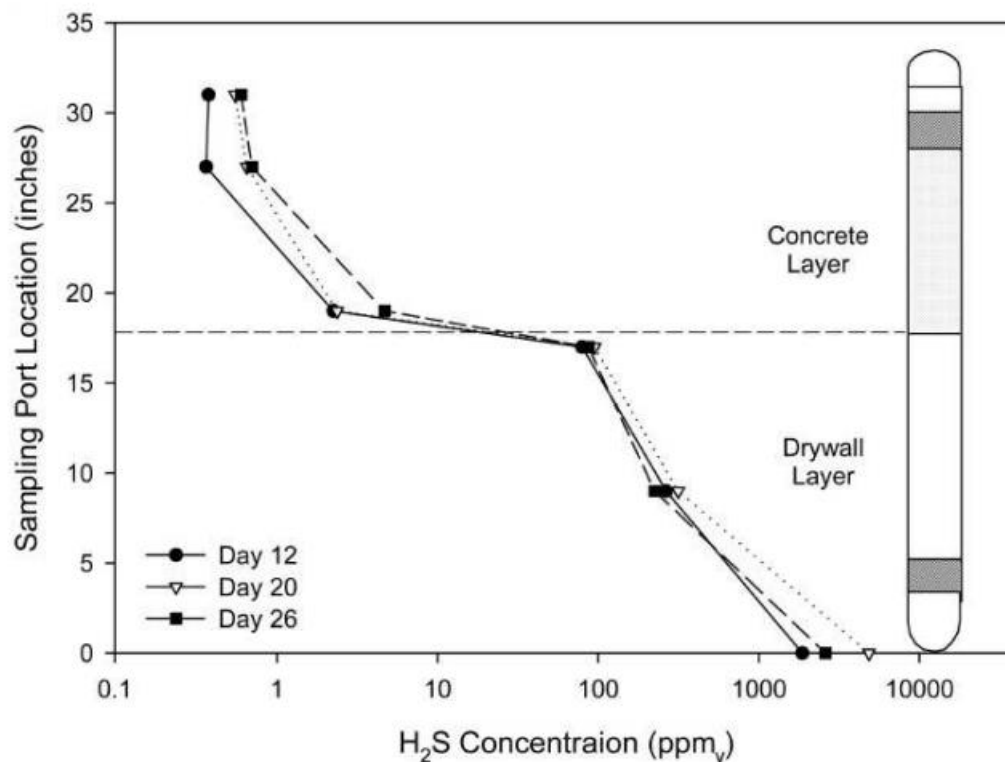
Yang et al, (2006) examined the amount of gas produced when gypsum boards were disposed

of along with other construction materials. Two experiments were performed using simulated landfill columns with gas extraction ports. The first landfill column measured the amount of gas produced when drywalls are disposed of alone and when disposed of with wood and crushed concrete. The simulated column used in this experiment is shown in Figure 12. The second column was composed solely of gypsum and crushed concrete wastes to determine the ability of crushed concrete to reduce emissions.



**Figure 12. Simulation of Column 1 (Yang et al, 2006)**

The results showed that when gypsum boards are disposed of alone, the boards decay and produce large amounts of sulfate ions which, in the presence of sulfate-reducing bacteria, give off large concentrations of gas capable of reaching up to 63,000 ppmv. When gypsum boards are disposed of with wood and crushed concrete, the amount of gas emitted ranged between 10,000 and 50,000 ppmv. On the other hand, in the second experiment when the crushed concrete layer was placed above the waste drywall layer, the amount of gas emitted was around 1 ppmv as shown in Figure 13.



**Figure 13. H<sub>2</sub>S Concentration profiles in simulated landfills from experiment 2 (Yang et al, 2006)**

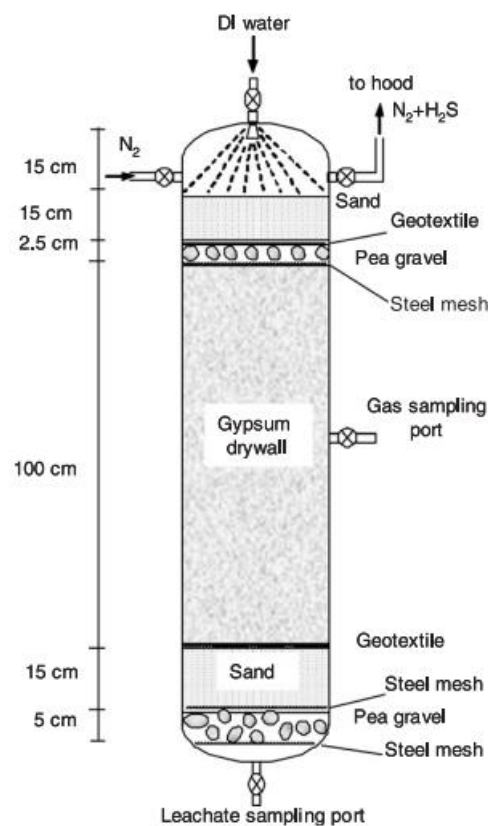
The resultant reduction in emission concentration can be seen to be due to the increase in pH given by the concrete that prevents the growth of sulfate reducing bacteria. Besides, the high concentration of calcium oxide (CaO) in the concrete matrix reacts with the hydrogen sulfide (H<sub>2</sub>S) gas to produce calcium sulfide (CaS). This reaction helps in suppressing the toxic gaseous emissions.



According to Yang et al., the amount of gas attributed to the disposal of drywall can be reduced either by adding crushed concrete directly to gypsum board waste or by using it as a cover material in landfill operations. Since construction and demolition (C&D) waste constitutes a significant portion of total solid waste, its disposal has become a major topic of discussion in the research community. Many studies have focused on inhibiting gas generation in landfills, particularly because the main cause of gas formation in C&D landfills is the biologically catalysed sulfate reduction of gypsum boards (Plaza et al., 2006). Therefore, it is necessary to

specifically monitor gas emissions in C&D landfills.

Further studies have been conducted to determine the effectiveness of different cover materials in reducing gas formation. Plaza et al. (2006) performed twelve experimental tests using simulated landfill columns that contained gypsum board waste under anaerobic conditions. In their study, five different cover materials were investigated: sandy soil, sandy soil mixed with lime, clayey soil, fine concrete with particle sizes smaller than 2.5 cm, and coarse concrete with particle sizes larger than 2.5 cm, as shown in Figure 14. Two additional columns without cover were included to compare and evaluate the performance of each material in terms of reducing gas emissions.

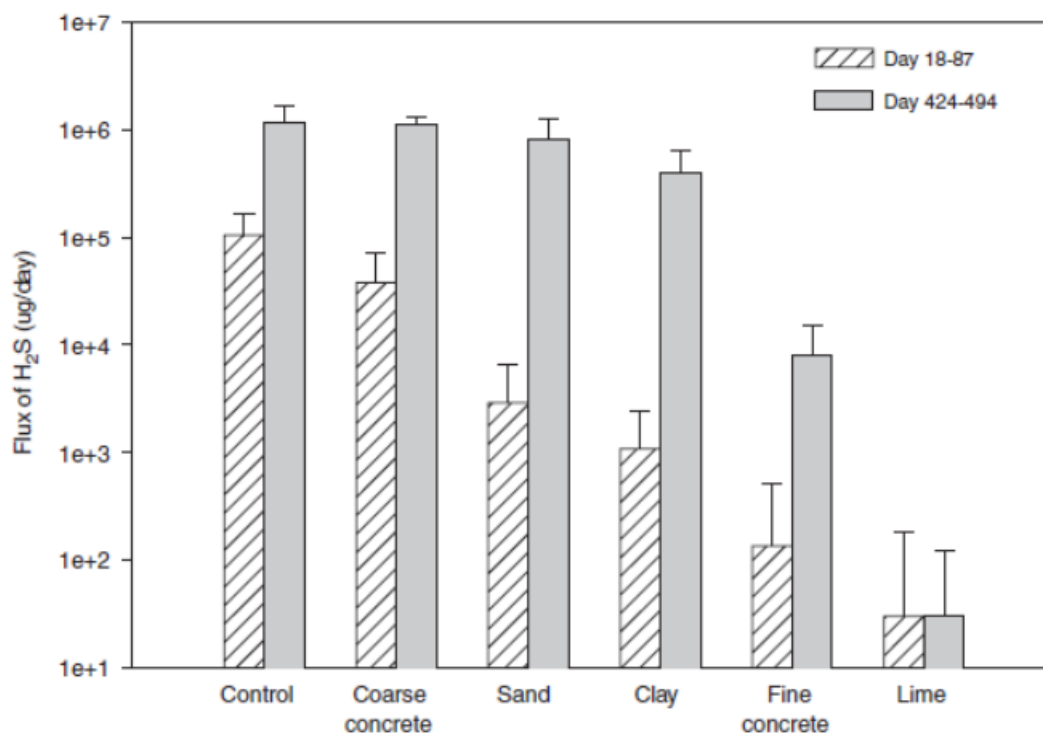


**Figure 14. Cross section of experimental column (Plaza et al, 2006)**

The results show a difference in efficiency of the gas reduction depending on the nature of cover material used. Sandy soil, lime and fine concrete had the highest efficacy with emission reduction level surpassing 99% (Plaza et al., 2006). The second most effective material was clayey soil that showed a reduction in 65 per cent. Sandy soil was the only one that achieved efficiency of about 30% but coarse concrete was worse and this could be attributed to the fact

that it has a bigger particle size (Plaza et al., 2006).

Figure 15 shows that the emissions rates varied with the various cover materials. In general, the environmental impact of gases produced when discarded gypsum drywall can be significantly reduced with the help of using the relevant cover layer. However, in terms of the environment, it is better to recycle gypsum boards since it considers the waste of gypsum boards as the valuable reuse opportunity, but not as merely a means of disposing of this waste.



**Figure 15. Average H<sub>2</sub>S emission rates measured during the initial continuous and modified flow stages (Plaza et al, 2006)**

#### IV.1.2 Air Pollution from Incineration

Incineration is also used intermittently in the treatment of gypsum waste, but it poses significant environmental concerns. Unless it is properly controlled, the burning of plasterboard can also release sulfur dioxide (SO<sub>2</sub>), which is one of the most common causes of acid rain, along with particulate matter and some trace metals, such as lead and cadmium (Morsali et al., 2024; Rivero et al., 2016).

To reduce the emission of harmful substances, the incineration plants should have modern technologies of emission control that include scrubbing flue gases and filtration of particles.

Their energy intensity and expensive capital and operation cost of these systems raise doubts on the viability of incineration as a waste-management approach to waste management.

### IV.1.3 Soil and Water Contamination

The other critical issue about plasterboard waste is that it may pollute soil and water systems. Gypsum dissolves in water, and when it is present in wet locations within landfills or in illegal dumping sites, it can leach sulfates and other heavy metals like lead and cadmium to the surrounding soil and groundwater (Xu et al. (2011)).

This pollution changes the soil chemistry, reduces the fertility, and retards plant growth. Furthermore, it has long-term health hazards as the toxins are deposited in the drinking and irrigation water.

### IV.1.4 Strategies for Mitigation

The reduction of the environmental consequences of plasterboard waste requires a multifaceted approach involving the establishment of recycling facilities, optimization of the regulatory framework, and the establishment of collaborative interactions among the stakeholders.

Some of the most promising sustainability actions include recycling efforts and closed-loop reuse. Waste gypsum may be reprocessed and used in the manufacture of new plasterboard, or it may be used as a soil repair. As shown in Table 21, recycled gypsum usually shows a slight reduction in the mechanical performance when compared to virgin gypsum; however, it leads to a significantly reduced level of carbon emissions and energy consumption (Jiménez Rivero et al. (2016); Eurogypsum 2008; Jiménez Rivero et al. (2017)).

**Table 22. Comparison of Natural vs. Recycled Gypsum**

<b>Property</b>	<b>Natural Gypsum</b>	<b>Recycled Gypsum</b>
<b>Purity</b>	80%	Varies (80–85%)
<b>Water Absorption</b>	Moderate	Slightly higher
<b>Mechanical Strength</b>	High	Slightly lower
<b>Carbon Footprint</b>	High (due to mining)	Lower
<b>Use in New Boards</b>	Widely used	Dependent on contamination and regulation

**Note.** Source : (Jiménez Rivero et al. (2016); Eurogypsum 2008 ; Jiménez Rivero et al. (2017)

## IV.2 Health and Safety Implications

### IV.2.1 Occupational Exposure and Worker Risks

The workers are exposed to occupational respirable dusts containing crystalline silica, gypsum and other additives. Continued exposure to such particulates has been associated with the occurrence of Chronic Obstructive Pulmonary Disease (COPD), bronchitis, asthma and silicosis. The demolition workers face other risks that are caused by the chemical additives such as adhesives and coating that cause dermal burns, eye damage and hypersensitivity.

### IV.2.2 Community Exposure and Environmental Justice

The disposal of plasterboard near residential areas, especially in low-income neighborhoods, exposes people to hydrogen sulfide (H<sub>2</sub>S) and air pollution. The symptoms that these emissions can cause are cephalalgia, nausea, and respiratory irritation. This unequal distribution of landfills and informal dumping areas raises some issues about environmental justice.

**Table 23. Health and Safety Risks from Plasterboard Waste**

Exposure Type	Affected Groups	Health Risks
Dust Inhalation	Construction workers	COPD, bronchitis, asthma
Gas Emission (H <sub>2</sub> S)	Nearby residents, landfill workers	Respiratory failure, headaches, nausea
Chemical Contact	Installers, demolition teams	Skin burns, eye irritation, silicosis
Noise & Debris	Public, urban areas	Stress, insomnia, cardiovascular strain

**Note** Source: Adapted from Chernysh et al. (2021); Yakhnenko et al. (2021); Cook et al. (2022).

## IV.3 Final Conclusion and Critical Reflection

As it has been explained in the current chapter, environmental and health impacts of plasterboard waste are not only large but also multifaceted. The mismanagement especially in landfill conditions has been reported to emit hydrogen sulfide (H<sub>2</sub>S) gas, ease sulfate and heavy metal leaching into soil and water bodies and release sulfide and heavy metals during burning.

All these environmental risks are compounded by high occupational and general health hazards, particularly in those situations that are typified by lax enforcement of the regulations and unchecked informal waste management activities.

The empirical data was based on the current scientific studies, which shows that the closed-loop gypsum recycling is the most sustainable approach to mitigation. Although recycled gypsum can have slightly decreased mechanical performance, its environmental benefits, i.e., decreased energy consumption and decreased emissions, are well-reported. However, the reality is that the rate of actual recycling is vastly different among nations, mostly because of economic, logistical and regulatory challenges as well. The problems that low- and middle-income countries (LMICs) face include inadequate infrastructure and the lack of public awareness.

The main gaps in the current research and implementation landscape are also identified in this chapter. These can be described as the lack of localized life-cycle assessment, a lack of comparative research on the performance of recycled gypsum, and a lack of internationally accepted standards of safe reuse. In addition, there is a lack of research on long-term health effects of the exposure to gypsum dust and the respective additives, particularly in the occupational context.

Going forward, the insights that are available in this paper demonstrate the need to:

- Development of sound policies that promote the material reuse and limit landfills.
- Direction of industrial investment into clean methods of demolition and the division of gypsum.
- Supporting research on innovation in recycling that focuses on low-cost systems that can be adapted locally; and
- Enhancing intersector cooperation to instil the principles of a circular economy in construction practice.

Plasterboard waste should not thus be seen as just another logistical hassle, but rather a strategic intervention point that can be used to reduce the environmental footprint of the construction industry. A successful solution to this waste stream can bring measurable improvements to a climate mitigation, population health, and resource saving.

## Chapter V. Second life for plasterboard

### V.1 Studies on Plasterboard Waste

The management of plasterboard waste has become a critical concern in sustainable construction, as large volumes are generated from both construction and demolition activities. Recent research increasingly emphasizes the concept of a “second life” for plasterboard, where waste materials are recovered, processed, and reused in new construction products. This approach not only reduces reliance on virgin gypsum but also mitigates environmental impacts associated with landfill disposal. Numerous studies have investigated the technical, economic, and environmental aspects of plasterboard recycling, highlighting innovative methods and practical challenges in implementing circular construction practices. The following section reviews these studies, providing insights into current advancements and opportunities for sustainable plasterboard management.

#### V.1.1 Valorizing Polyurethane Waste in Gypsum Ceiling Tiles

Rodrigo-Bravo et al. (2025) investigated the integration of post-consumer polyurethane (PU) foam waste and plasterboard residues into gypsum ceiling tiles, targeting a circular economy framework in building materials within the broader context of circular economy principles in construction materials. Using a combination of virgin gypsum, recycled gypsum, and polyurethane foam waste (PUW), they produced composite boards and evaluated their physical and mechanical properties. The study reported that the incorporation of up to 30% PUW led to a reduction in density (11.5–20.4%), thermal conductivity (up to 37%), and bending strength (a decrease of 12–18%). However, despite the slight drop in mechanical performance, all samples complied with UNE standards for non-structural ceiling tiles. The embodied energy and carbon footprint of the composites were also significantly reduced, achieving nearly 30% fewer CO<sub>2</sub> emissions than conventional boards. The authors concluded that minor process optimization could further improve strength properties, and the use of PUW in gypsum boards presents a viable path for waste valorization and emission reduction in construction materials.

#### V.1.2 Recycled Gypsum in Interior Plaster: Mechanical and Environmental Performance

Puerto et al. (2024) examined the feasibility of replacing commercial gypsum with recycled gypsum of plasterboards in order to apply commercially as an architectural plaster. They decided to synthesize recycled gypsum (RG) by milling and subsequently tested its effects

against commercial gypsum (CG) with regard to setting time, water retention, compressive strength, and workability. Setting time of RG plaster was only slightly different from CG (23.6 vs. 24.1 min) and at 28 days, the compressive strength has been capable of becoming 3.6 MPa which is very near to 3.9 MPa recorded in CG. The paper further addressed the economic and environmental advantages, which showed that the reduction in cost may reach 13.7 percent, and the CO<sub>2</sub> equivalent emissions will also be lower since there will be less energy-centered collecting raw materials. Impurities such as weakness and lack of homogeneity were a problem related to controlling the size of particles and getting rid of paper residues, something that the authors highlighted. All in all, their results portray that RG can become a durable and dependable alternative to CG in the finishing of interior plasters retaining the usability.

### **V.1.3 Composting Applications of Clean Drywall Waste in Agriculture**

Ndukwe and Yuan (2016) performed the review of gypsum drywall recycling as a compost bulking agent in North America, evaluated environmental, technical, regulatory implications. In their study, they emphasized on the drywall composition that mainly comprises of calcium sulphate dihydrate (93%) and paper liner (7 percent), which promotes the compost with calcium and sulfur. The authors have considered case studies such as a large pilot project in Columbia, Missouri, diverting more than 700 tons/year of dry wall into municipal compost. Bench-scale tests showed that drywall added drywall led to an increase in compost porosity, increased odor control and a reduction in drying time when used clean and free of contaminants (e.g. joint compound, adhesives, paint). The paper has also addressed the issue related to the potential hydrogen sulfide emissions during the anaerobic landfilling of drywall as well as the necessity to regulate in order to differentiate between the clean construction waste and possibly dangerous demolition rubble. Scale up of this solution was supported by the authors in suggesting source-separated collection systems and working collaboratively with farmers because demonstrating that drywall can be considered a valuable resource rather than waste.

### **V.1.4 Life Cycle Assessment of Plasterboard Production in the UK**

Morsali et al. (2024) carried out a detailed study with life cycle assessment (LCA) assessing the environmental performance of the plasterboard production in the UK under three scenarios of sourcing requirements: virgin and recycled gypsum and synthetic gypsum made using flue gas desulfurization (FGD). They discovered that recycling of gypsum can cut global warming potential (GWP) by 69%, energy usage by 40 % and volume of water by 32%, according to the results they obtained using CML and IPCC impact methods of studying the

impact of use of above 50 % of recycled gypsum relative to 100 percent virgin gypsum production. Transportation and end-of-life scenarios were also modeled using an LCA model, which demonstrated that when regionally sourced recycled gypsum was used instead of imported virgin gypsum, the former better performed according to all the environmental categories. The research encouraged the adoption of circular economy principles supported by legislative requirements on the recycled content in building materials. Their findings outline policy changes on a more comprehensive level to foster gypsum recycling infrastructure and the fact that environmental and financial motivations are closely related to the effects of sustainable plasterboard production.

### **V.1.5 Geotechnical Reuse of Plasterboard Manufacturing Offcuts**

Imteaz and Arulrajah (2019) evaluated the geotechnical feasibility of the use of a particular waste, whose component was manufacturing offcut, as a structural fill in the infrastructure field. The study was conducted by compacting gypsum board powder (GBP) and adding lime, fly ash, and bottom ash into mixtures and testing them on unconfined compressive strength (UCS) and California Bearing Ratio (CBR) tests among others. The results showed that the GBP-lime mixtures will give CBR values between 16%-27%, a sufficient level to construct the subgrade layers in a road. It was moisture sensitive and had potential to swell, especially in the conditioned state with bottom ash. According to the conclusions drawn by the authors, GBP could be used safely in temporary roads, embankments and backfills, and there was the bonus of saving quarrying virgin aggregates. Their results focus on an opportunity pathway in terms of using gypsum waste in large-scale civil engineering works to ensure that they support structural integrity and carry out with minimum impact to the environment.

### **V.1.6 Environmental Comparison of Natural vs. Recycled Gypsum**

Pedreño-Rojas et al. (2020) presented a comparative life cycle analysis (LCA) of natural gypsum mining versus the use of recycled gypsum from post-consumer plasterboard. Conducted in Spain, their study used the IMPACT 2002+ method and found that recycled gypsum significantly outperformed natural gypsum in most environmental categories. Notably, global warming potential (GWP) was reduced by 43%, terrestrial ecotoxicity by 38%, and water use by over 50%. These results were attributed to the energy-intensive processes of mining and drying virgin gypsum, compared to the less resource-demanding recovery of recycled material. The authors modeled a hybrid sourcing approach, proposing that up to 80% of national demand could be met with recycled gypsum. They advocated for regional collection hubs, improved

demolition sorting practices, and policy incentives to scale gypsum recycling and replace mineral extraction with closed-loop material flows.

### V.1.7 European Energy Analysis of Plasterboard Recycling Scenarios

Rivero et al. (2016) performed an energy and mass balance assessment of plasterboard recycling across Europe, aiming to quantify the environmental and operational benefits of replacing virgin gypsum with recycled content. Their system-wide model indicated a 30–45% reduction in energy consumption over the full life cycle of plasterboard products when recycled gypsum was used. Landfill diversion rates reached 90% in optimized scenarios. The analysis emphasized that transportation logistics and regional collection infrastructure were key factors influencing overall efficiency. By advocating for centralized recycling facilities and harmonized EU recycling policies, the authors demonstrated that widespread adoption of plasterboard recycling could support circular economy goals, reduce energy intensity, and reduce dependency on non-renewable gypsum reserves as shown in Table 23.

**Table 24. Key Performance Indicators for Plasterboard Recycling: Conventional vs. Optimized Scenarios**

	<b>Conventional Scenario (Virgin Gypsum / Landfilling)</b>	<b>Optimized Scenario (Recycled Gypsum / Centralized Recycling)</b>
<b>Primary Raw Material</b>	Virgin Gypsum	Recycled Gypsum
<b>Energy Consumption (Full Life Cycle)</b>	Higher	30–45% Reduction (Indicated by the system-wide model)
<b>Landfill Diversion Rate</b>	Low (High landfilling rates observed in many EU countries)	Reached 90% (In optimized scenarios)
<b>Resource Dependency</b>	High dependency on non-renewable gypsum reserves	Reduced dependency on non-renewable gypsum reserves
<b>Logistics &amp; Infrastructure</b>	Decentralized or lacking adequate regional collection infrastructure	Relies on centralized recycling hubs and harmonized collection infrastructure

**Note.** Data adapted from Jiménez Rivero, A., Sathre, R., & García Navarro, J. (2016).

### **V.1.8 Hybrid Composite Panels with Recycled Gypsum and Ceramic Waste**

Geraldo et al. (2018) explored the fabrication of gypsum-based construction panels incorporating recycled ceramic and brick waste, forming a hybrid composite. The material mix of 60% gypsum, 20% ceramic waste, and 20% brick dust yielded composite boards with compressive strength values ranging from 5.1 to 5.9 MPa, acoustic insulation up to 41 dB, and thermal conductivity around 0.2 W/m·K. These metrics were deemed suitable for internal partitions and ceiling applications. The use of brick and ceramic residues also enhanced the board's microstructural integrity and reduced shrinkage. Environmental impact analysis indicated a 35% reduction in carbon emissions compared to conventional gypsum panels. The authors highlighted the potential for regional prefabrication of eco-panels using construction debris, thereby supporting urban circular economies and reducing material transport costs.

### **V.1.9 Regional Management Strategies for Gypsum Wallboard Recycling**

Emma Marvin's (2000) field report on Vermont's gypsum wallboard recycling offered a pragmatic roadmap for local waste management programs. Focused on clean drywall waste from new construction sites, Marvin evaluated strategies such as donation, resale, recycling, and composting. One case study at Smugglers' Notch Resort saved \$60/ton by recycling drywall rather than landfilling it. She also identified regional processors like GP-Gypsum and New West Gypsum as key players, noting their capacity to reintroduce clean drywall into new board production. Furthermore, Marvin explored agricultural reuse, citing improved compost quality and calcium enrichment in field trials. Her policy recommendations stressed the need for clear material definitions, regulatory support, and logistical coordination between contractors, farmers, and recyclers. Even decades later, this report remains a foundational template for circular construction waste strategies in rural and semi-urban areas.

Table 25. Summary of Key Studies on Plasterboard Recycling and Reuse

Author(s), Year	Type of Study	Main Results	Limitations
<b>Rodrigo-Bravo (2025)</b>	Experimental tiles using polyurethane and recycled gypsum	Improved insulation; some samples met strength standards.	Not all mixes viable; limited scalability.
<b>Puerto (2024)</b>	Mechanical testing of recycled gypsum from C&D waste (Colombia)	Good compressive strength; cost-effective; lower environmental burden.	Colombian context; no durability testing.
<b>Ndukwe &amp; Yuan (2016)</b>	Review of drywall reuse and composting	Recycling prevents H <sub>2</sub> S gas formation ; composting adds soil nutrients.	H <sub>2</sub> S risks, U.S.-centric; lacks EU-specific data or LCA.
<b>Morsali (2024)</b>	UK-based LCA	Highest impacts from raw gypsum supply and transport; toxicity category dominant.	UK-specific study; lacks scenario modeling for alternative recycling rates.
<b>Imteaz &amp;</b>	Geotechnical Testing	Recycled gypsum safe	Focuses on short-term

<b>Arulrajah (2019)</b>		and effective for road base and backfill.	safety; lacks carbon accounting or lifecycle-based impact assessment.
<b>Pedreño-Rojas (2020)</b>	LCA comparing natural vs. recycled gypsum in Spain	Recycled gypsum reduced environmental impacts by 41–58%.	Based on a single industrial site (Jaén); no transport optimization.
<b>Jiménez-Rivero et al. (2016)</b>	EU-27 material flow and LCA scenarios	Recycling gypsum significantly reduces greenhouse gas emissions, though energy savings are limited.	Best-case recycling only 18.7%; assumes idealized logistics.
<b>Geraldo (2018)</b>	Pressing recycled gypsum with red ceramic and porcelain waste into dense composites	Strong, low-porosity bricks met standards.	Limited to non-structural use; no LCA or field performance data.
<b>Marvin (2000)</b>	Field Report (USA)	\$60/ton savings, compost enrichment; reuse in agriculture viable; H <sub>2</sub> S risk if landfilled.	Outdated, limited regional scope.

## V.2 Cross-Study Analysis and Critical Comparisons

### V.2.1 Environmental Performance and Scope of LCA.

Environmental assessments were the strictest (Pedreño-Rojas et al.; Morsali et al.; Jimenez-Rivero et al.) as they used life-cycle assessment (LCA) to measure the effects of gypsum recycling. The three papers find significant declines in climate indicators; however, each of them identifies different drivers:

- Pedreño-Rojas et al. document that the total environmental impact in the case of recycled gypsum is reduced by more than 40% when the product is applied to industrial conditions in Spain. This outcome is not directly proportional to smaller or decentralized

activities like those that are prevalent in Portugal, so one should be cautious.

- Jiménez-Rivero et al. extrapolate the discussion to the EU-27 level and find that recycling can reduce greenhouse gas emissions, but it fails to reduce primary energy use significantly. The advantages of mining are counterbalanced by transport and pre-processing which is an important lesson in geographically spread areas like Portugal.
- The article by Morsali et al. highlights the hottest spots of toxicity, specifically those related to raw gypsum mining and processing that is energy-intensive, thus making the case of substituting the material and creating decarbonized production and delivery chains strong.

### V.2.2 Mechanical and Functional Performance of Recycled Gypsum Recycled

Gypsum can be structurally or functionally equivalent to virgin materials, which are confirmed by experimental studies (Puerto et al.; Rodrigo-Bravo et al.; Geraldo et al.; Erbs et al.), although this is not always the case:

- Puerto et al. validate the technical feasibility of recycled gypsum in Colombian plaster and attain a satisfactory compressive strength.
- Rodrigo-Bravo et al. show that thermal performances could be improved by -16% of thermal conductivity and warn that not all mixes were structural.
- Geraldo et al. arrive at forming blocks with the use of ceramic waste and recycled gypsum with compressive strengths of more than 12 Mpa, which exceeds the Brazilian minimum requirements.
- Erbs et al. add biomass ash to the gypsum matrix, which improves insulation qualities and decreases weight and makes them more suitable when used as non-load-bearing panels.

Most importantly, Geraldo et al., and Puerto et al., only affirm structural adequacy, but Rodrigo-Bravo and Erbs are aimed at functional reuse (e.g., insulation). This branching suggests a strategy design choice: structural versus performance reuse pathways.

### V.2.3 Circularity Beyond Structural Reuse.

A few research investigated non-construction reuse (Marvin; Ndukwe & Yuan; Imteaz

et al.):

- Imteaz et al. confirm the application of gypsum recycled in road subgrades and drainage layers, with no leaching of toxins and therefore is a low-barrier application of non-recyclable fractions.
- Ndukwe + Yuan and Marvin support the idea of composting or reusing agrarian, in which case, drywall supplements soils with sulfur and calcium, thus increasing their fertility. But Marvin cautions that landfill anaerobic fermentation forms H<sub>2</sub>S which is a powerful toxin and is a key motivation to divert.

These applications offer vital pressure relief to overloaded recycling flows, especially where the material reprocessing infrastructure is still limited like in Portugal where infrastructures are scarce.

#### **V.2.4 Implementation Barriers: Logistics, Policy and Scale.**

Although technical capability is exhibited in the contexts, its implementation is limited by:

- Transport and logistics: Jiménez-Rivero et al. did not find any energy savings associated with recycling because of high energy demands in the collection and pre-processing phase.
- Policy fragmentation: The contribution of Marvin and Ndukwe of the United States to the topic suggests that consistent policies are required and this still applies to the European Union where recycling mandates are frequently not upheld.
- Scaling constraints: Erbs, Rodrigo-Bravo, and Puerto all are still laboratory-scale experiments. In Southern Europe, there is a significant down-step in pilot, or industrial-scale demonstrations.

### **V.3 Conclusion: Enabling a Circular Gypsum Strategy in Portugal and the EU**

The reviewed empirical and analytical evidence substantiates the fact that the recycling of gypsum significantly minimizes the environmental impact especially with regard to greenhouse-gas emission, land use, and toxicity. However, these advantages can be scaled, which is dependent on infrastructure, policy, and regional adaptation. In the case of Portugal, the way forward will involve:

1. Localised recycling centres in order to reduce transportation costs.

2. Various reuse options: construction (blocks, panels), geotechnical (fill, bedding), and agricultural (composting).

3. Gypsum policy co-ordination with EU circular-economy objectives - mandatory gypsum recycling quotas in CDWs.

4. To increase the range of performance applications, hybrid composites (e.g., gypsum + ceramic, gypsum + ash).

5. Gypsum Procurement incentives into recycled gypsum used in public construction.

Through these techniques, Portugal will be able to transform into an exemplary Southern European role model of circular construction, using gypsum not as waste, but as a renewable resource, in an optimised material economy.

## Chapter VI. Conclusion and Future Works

Plasterboard continues to play a central role in contemporary construction owing to its versatility, efficiency, and cost-effectiveness. However, its environmental implications, from production to disposal, underline the critical need for sustainable practices across its entire lifecycle. Advances in recycling technologies and innovative applications for recycled gypsum have demonstrated significant potential to reduce landfill dependency, minimize environmental hazards, and promote resource efficiency. Utilizing recycled plasterboard materials for applications like soil stabilization exemplifies how construction waste can be transformed into valuable resources.

Looking forward, future research could prioritize the scaling up of recycling initiatives and the development of cost-effective, efficient technologies to process plasterboard waste on a larger scale. Research should also prioritize the development of eco-friendly additives and alternative materials to further reduce reliance on virgin resources while maintaining or improving material performance. Effective management will depend on stronger collaboration between governments and industries, including regulatory support, , promote public awareness, and encourage sustainable construction practices, including the use of recycled materials.

The adoption of circular economy principles in plasterboard production and disposal can significantly reduce its environmental impact, contributing to broader global sustainability goals. By aligning innovation, policy, and industry collaboration, the construction sector can balance its growth with environmental stewardship, paving the way for a sustainable and responsible future.

## References

## References

1. Al-Homoud, M. S. (2005). Performance characteristics and practical applications of common building thermal insulation materials. *Building and Environment*, 40(3), 353–366. <https://doi.org/10.1016/j.buildenv.2004.05.013>
2. Ali, S. H. (2014). Social and environmental impact of the rare earth industries. *Resources*, 3(1), 123–134. <https://doi.org/10.3390/resources3010123>
3. Alkamaly, H. J., & Albadry, A. M. (2025). Acoustic insulation of residential units in high-rise buildings. *Journal of Engineering (Baghdad University)*, 31(2), 44–57. <https://joe.uobaghdad.edu.iq/index.php/main/article/view/3672>
4. Asdrubali, F., Schiavoni, S., & Horoshenkov, K. (2012). A review of sustainable materials for acoustic applications. *Building Acoustics*, 19(4), 283–311. <https://doi.org/10.1260/1351-010x.19.4.283>
5. Arroyo, F. N., Christoforo, A. L., & Salvini, V. R. (2020). Development of plaster foam for thermal and acoustic applications. *Construction and Building Materials*, 258, 119608. <https://doi.org/10.1016/j.conbuildmat.2020.120800>
6. ASTM International. (2020). ASTM C22/C22M – Standard Specification for Gypsum. ASTM International.
7. Balador, Z., Gjerde, M., Isaacs, N., & Imani, M. (2018). Thermal and acoustic building insulations from agricultural wastes. In *Handbook of Ecomaterials* (pp. 145–167). Springer. [https://www.researchgate.net/publication/324136627\\_Thermal\\_and\\_Acoustic\\_Building\\_Insulations\\_from\\_Agricultural\\_Wastes](https://www.researchgate.net/publication/324136627_Thermal_and_Acoustic_Building_Insulations_from_Agricultural_Wastes)
8. Bogner, J. et al. (2008). Waste Management. In *Climate Change 2007: Mitigation of Climate Change (IPCC Fourth Assessment Report)*. <https://www.ipcc.ch/site/assets/uploads/2018/02/ar4-wg3-chapter10-1.pdf>
9. BuildingGreen, Inc. (2012, March 14). Gypsum board: Are our walls leaching toxins? Retrieved from <https://www.buildinggreen.com/blog/gypsum-board-are-our-walls-leaching-toxins>
10. Bunzel, J.-M. (2024). MUEG Mitteldeutsche Umwelt und Entsorgung GmbH Grosspösna gypsum recycling plant. AT Minerals. Retrieved from <https://www.at-minerals.com/en/artikel/mueg-mitteldeutsche-umwelt-und-entsorgung-gmbh-grosspoesna-gypsum-recycling-plant-4064706.html>
11. Chen, Z., Feng, Q., Yue, R., Chen, Z., Moselhi, O., Soliman, A., Hammad, A., & An, C. (2022). Construction, renovation, and demolition waste in landfill: a review of waste characteristics, environmental impacts, and mitigation measures. *Environmental Science and Pollution Research*, 29, 46509–46526. <https://doi.org/10.1007/s11356-022-20479-5>

## References

12. Chernysh, Y., Yakhnenko, O., Chubur, V., & Roubík, H. (2021). Phosphogypsum Recycling: A Review of Environmental Issues, Current Trends, and Prospects. *Applied Sciences*, 11(4), 1575. <https://doi.org/10.3390/app11041575>
13. Cook, E., Velis, C. A., & Black, L. (2022). Construction and Demolition Waste Management: A Systematic Scoping Review of Risks to Occupational and Public Health. *Frontiers in Sustainability*, 3, 924926. <https://doi.org/10.3389/frsus.2022.924926>
14. Cuce, E., Cuce, P. M., Wood, C. J., & Riffat, S. B. (2014). Toward aerogel based thermal superinsulation in buildings: A comprehensive review. *Renewable and Sustainable Energy Reviews*, 34, 273–299. <https://doi.org/10.1016/j.rser.2014.03.017>
15. Cuccagna, E. G. F., & Mignot, V. (2024). Excavated earth incorporating hemp and tannin for the manufacture of thermally insulating mortars for wall panels. *Spring Convention and Sustainable Materials Proceedings*. [https://link.springer.com/chapter/10.1007/978-3-031-70277-8\\_15](https://link.springer.com/chapter/10.1007/978-3-031-70277-8_15)
16. Curtis, P. G., Slay, C. M., Harris, N. L., Tyukavina, A., & Hansen, M. C. (2018). Classifying drivers of global forest loss. *Science*, 361(6407), 1108–1111. <https://doi.org/10.1126/science.aau3445>
17. Environment Agency, Waste Acceptance at Landfills, November 2010, [https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/296422/geo1\\_110btew-e-e.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/296422/geo1_110btew-e-e.pdf)
18. Environmental Protection Agency’s Waste Reduction Model, <https://www.epa.gov/waste-reduction-model/versions-waste-reduction-model>
19. European Commission. (2018). Best Available Techniques (BAT) Reference Document for Large Combustion Plants.
20. European Environment Agency. (2020). Construction and demolition waste management in Europe: Challenges and opportunities in circularity (EEA Report No. 25/2020). <https://www.eea.europa.eu/en/analysis/publications/construction-and-demolition-waste-challenges>
21. Eurogypsum aisbl. (n.d.). The gypsum industry – About gypsum. Retrieved from <https://eurogypsum.org/the-gypsum-industry/about-gypsum/>
22. Eurogypsum. (2008). *What is Gypsum?* Environment and Raw Material Committee. Brussels: Eurogypsum. <https://www.eurogypsum.org/wp-content/uploads/2015/04/whatisgypsum.pdf>
23. Eurogypsum. (2015). *Living with gypsum — A guide for architects and engineers*. Brussels: Eurogypsum. Retrieved from <https://www.eurogypsum.org/wp-content/uploads/2015/04/livingwithgypsum.pdf>

## References

24. FAO & UNEP. (2020). The State of the World's Forests 2020: Forests, biodiversity and people. Food and Agriculture Organization of the United Nations. <https://doi.org/10.4060/ca8642en>
25. Farag, S., Farag, Y., & Attia, M. (2025). Recycling technologies for brominated flame-retardant plastics in e-waste. *Cleaner Waste Systems*, 2, 100152. <https://doi.org/10.1016/j.clwas.2025.100418>
26. Fawole, A. A., Orikpete, O. F., & Ehiobu, N. N. (2023). Climate change implications of electronic waste: Strategies for sustainable management. *Bulletin of the National Research Centre*, 47, Article 128. <https://doi.org/10.1186/s42269-023-01124-8>
27. Fediuk, R., Amran, M., Vatin, N., Vasilev, Y., & Lesovik, V. (2021). Acoustic properties of innovative concretes: A review. *Materials*, 14(2), 398. <https://doi.org/10.3390/ma14020398>
28. Frayer, L. (2019, July 6). A Day's Work On Delhi's Mountain of Trash. NPR. <https://www.npr.org/sections/goatsandsoda/2019/07/06/738965440>
29. Gautam, M., & Agrawal, M. (2020). Greenhouse gas emissions from municipal solid waste management: A review of global scenario. In *Carbon Footprint Case Studies* (pp. 59–85). Springer. [https://doi.org/10.1007/978-981-15-9577-6\\_5](https://doi.org/10.1007/978-981-15-9577-6_5)
30. Georgia-Pacific Gypsum LLC. (2010). Typical process of manufacturing gypsum board.
31. Gordon, P. (2020). Fire-resistance test on services penetrating a plasterboard wall (Report No. FSP 2084). CSIRO Infrastructure Technologies. <https://bossfire.com.au/wp-content/uploads/2023/12/CSIRO-FSP-2084.pdf>
32. Gouda, A., Merhi, N., Hmadeh, M., & Cecchi, T. (2025). Sustainable strategies for converting organic, electronic, and plastic waste from municipal solid waste into functional materials. *Global Challenges*. <https://doi.org/10.1002/gch2.202400240>
33. Goh, P. G., Maghfouri, M., Onn, C. C., & Loo, S. C. (2022). Life cycle assessment on recycled e-waste concrete. *Case Studies in Construction Materials*, 17, e01030. <https://doi.org/10.1016/j.cscm.2022.e01412>
34. Gypsum Recycling International, <http://www.gypsumrecycling.biz/>
35. Henke, M. (2022). An exploration of architectural acoustics and design in commercial recording studios. California State University Monterey Bay. [https://digitalcommons.csumb.edu/caps\\_thes\\_all/1322/](https://digitalcommons.csumb.edu/caps_thes_all/1322/)
36. Hongisto, V., Saarinen, P., Alakoivu, R., & Hakala, J. (2022). Acoustic properties of commercially available thermal insulators—An experimental study. *Journal of Building Engineering*, 58, 105942. <https://doi.org/10.1016/j.jobbe.2022.104588>

## References

37. Hong, J., Shi, W., Wang, Y., Chen, W., & Li, X. (2015). Life cycle assessment of electronic waste treatment. *Waste Management*, 38, 357–365. <https://doi.org/10.1016/j.wasman.2014.12.022>
38. Hopfe, C. J., & Hall, M. R. (2012). Fabric insulation, thermal bridging and acoustics in modern earth buildings. In *Modern Earth Buildings* (pp. 55–82). Elsevier. <https://doi.org/10.1533/9780857096166.1.41>
39. Imteaz, M. A., Arulrajah, A., & Maghool, F. (2020). Environmental and geotechnical suitability of recycling waste materials from plasterboard manufacturing. *Waste Management & Research*, 38(4), 383–391. <https://doi.org/10.1177/0734242X19881213>
40. INPE – OBT. PRODES – Programa de monitoramento dos desmatamentos na Amazônia. <http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes>
41. IPCC. (2019). *Climate Change and Land: An IPCC Special Report*. <https://www.ipcc.ch/srccl/>
42. Jiménez Rivero, A., & García Navarro, J. (2017). Characterization of quality recycled gypsum and implications for gypsum plasterboard manufacturing within the circular economy context. *Journal of Cleaner Production*, 164, 281–292. <http://dx.doi.org/10.3989/mc.2017.06016>
43. Jiménez Rivero, A., Sathre, R., & García Navarro, J. (2016). Life cycle energy and material flow implications of gypsum plasterboard recycling in the European Union. *Resources, Conservation and Recycling*, 108, 171–181. <https://doi.org/10.1016/j.resconrec.2016.01.014>
44. Just, A., Schmid, J., & König, J. (2010). Gypsum plasterboards used as fire protection: Analysis of a database (SP Report 2010:29). SP Technical Research Institute of Sweden. <https://www.traguiden.se/globalassets/forskning/brand---rapporter/gypsum-plasterboards-used-as-fire-protection---analysis-of-a-database.pdf>
45. Kang, F. (2023, December 11). Fire resistance test procedure and plasterboard's performance. GIB. <https://www.gib.co.nz/gib-news/articles/fire-resistance-test-procedure-and-plasterboard-s-performance>
46. Karataş, M., Erzen, B., & Orhan, R. (2025). Innovative insulation materials: A comprehensive review of current trends, challenges, and future directions in sustainable building technologies. *Polymer-Plastics Technology and Materials*, 64(5), 247–273. <https://doi.org/10.1080/25740881.2025.2472378>
47. Klemczak, B., Kucharczyk-Brus, B., & Sulimowska, A. (2024). Historical evolution and current developments in building thermal insulation materials—A review. *Energies*, 17(22), 5535. <https://doi.org/10.3390/en17225535>
48. Korjakins, A., Sahmenko, G., & Lapkovskis, V. (2025). A short review of recent innovations in acoustic materials and panel design: Emphasizing wood composites for

## References

- enhanced performance and sustainability. *Applied Sciences*, 15(9), 4644.  
<https://doi.org/10.3390/app15094644>
49. Košny, J., & Yarbrough, D. W. (2022). Short history of thermal insulation and radiation control technologies used in architecture. In *Thermal Insulation and Radiation Control Technologies in Buildings* (pp. 1–32). Springer. [https://doi.org/10.1007/978-3-030-98693-3\\_1](https://doi.org/10.1007/978-3-030-98693-3_1)
50. Marvin, E. (2000). Gypsum Wallboard Recycling and Reuse Opportunities in the State of Vermont. Waste Management Division, Vermont Agency of Natural Resources.  
<https://p2infohouse.org/ref/23/22738.pdf>
51. Massoudinejad, M., Amanidaz, N., & Santos, R. M. (2019). Use of municipal, agricultural, industrial, construction and demolition waste in thermal and sound building insulation materials: A review article. *International Journal of Environmental Health Engineering*, 8(1), 1–15. <https://doi.org/10.1007/s40201-019-00380-z>
52. Mohammed, A. S., & Meincken, M. (2023). Thermal and acoustic insulation properties of wood plastic composites (WPCs) for interior housing applications. *European Journal of Wood and Wood Products*, 81(3), 567–581. <https://doi.org/10.1007/s00107-022-01897-1>
53. Morsali, S., Rakhshanbabanari, K., Osmani, M., Cavalaro, S., Gutai, M., Castro-Díaz, M., Parker, B., Sparkes, J., Needham, P., Newport, S., & Massey, A. (2024). Life Cycle Assessment of Plasterboard Production: A UK Case Study. *Sustainability*, 16(9), 3564. <https://doi.org/10.3390/su16093564>
54. Neri, M. (2022). Thermal and acoustic characterization of innovative and unconventional panels made of reused materials. *Atmosphere*, 13(11), 1825.  
<https://doi.org/10.3390/atmos13111825>
55. Ndukwe, I., & Yuan, Q. (2016). Drywall (Gyproc Plasterboard) Recycling and Reuse as a Compost-Bulking Agent in Canada and North America: A Review. *Recycling*, 1(4), 311–320. <https://doi.org/10.3390/recycling1030311>
56. Ouda, M., Abu Sanad, A. A., Abdelaal, A., & Krishna, A. (2025). A comprehensive review of sustainable thermal and acoustic insulation materials from various waste sources. *Buildings*, 15(16), 2876. <https://doi.org/10.3390/buildings15162876>
57. Pacheco-Torgal, F., Tam, V. W. Y., Labrincha, J. A., & Ding, Y. (2013). *Handbook of recycled concrete and demolition waste*. Woodhead Publishing.  
<http://ndl.ethernet.edu.et/bitstream/123456789/6533/1/Handbook%20of%20Recycled%20Concrete%20and%20Demolition%20Waste.pdf>
58. Pedreño-Rojas, M. A., Fořt, J., Černý, R., & Rubio-de-Hita, P. (2020). Life cycle assessment of natural and recycled gypsum production in the Spanish context. *Journal of Cleaner Production*, 253, 120056. <https://doi.org/10.1016/j.jclepro.2020.120056>

## References

59. Pedreño-Rojas, M. A., De Brito, J., Flores-Colen, I., Pereira, M. F. C., & Rubio-de-Hita, P. (2020). Influence of gypsum wastes on the workability of plasters: Heating process and microstructural analysis. *Journal of Building Engineering*, 29, 101143. <https://doi.org/10.1016/j.jobe.2019.101143>
60. Pedroso, M., De Brito, J., & Silvestre, J. D. (2017). Characterization of eco-efficient acoustic insulation materials (traditional and innovative). *Construction and Building Materials*, 139, 142–151. <https://doi.org/10.1016/j.conbuildmat.2017.02.132>
61. Petrone, C., Magliulo, G., & Manfredi, G. (2016). Mechanical properties of plasterboards: experimental tests and statistical analysis. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0001630](https://doi.org/10.1061/(ASCE)MT.1943-5533.0001630)
62. Plaza, C., Xu, Q., Townsend, T., Bitton, G., & Booth, M. (2007). Evaluation of alternative landfill cover soils for attenuating hydrogen sulfide from construction and demolition (C&D) debris landfills. *Journal of Environmental Management*, 84(3), 314–322. <https://doi.org/10.1016/j.jenvman.2006.06.001>
63. Puerto, J. D., Uribe, S., Ayala, L., Padilla, A., & Rodriguez, A. (2024). Reliability of Reusing Gypsum Flat Board Grinded Waste as a Conventional Plaster Replacement for Buildings. *Sustainability*, 16(18), 7889. <https://doi.org/10.3390/su16187889>
64. Ramteke, J., Rathore, K., & Supe, J. D. (2025). Green concrete incorporating industrial waste and e-waste: A review of compressive strength, CO<sub>2</sub> emissions, and replacement levels. *Asian Journal of Civil Engineering*. <https://doi.org/10.1007/s42107-025-01284-0>
65. Rodrigo-Bravo, A., Pavía, S., Calderón Carpintero, V., Alameda Cuenca-Romero, L., & Gutiérrez-González, S. (2025). Valorisation of gypsum boards with polyurethane waste to promote their circular economy. *Resources, Conservation & Recycling Advances*, 25, 200240. <https://doi.org/10.1016/j.rcradv.2024.200240>
66. Rockström, J., et al. (2009). A safe operating space for humanity. *Nature*, 461(7263), 472–475. <https://doi.org/10.1038/461472a>
67. Robert, U. W., Etuk, S. E., Agbasi, O. E., & Oyegoke, D. A. (2025). Sustainable ceiling panels: Exploring the potentials of groundnut shell and sugarcane bagasse-modified plaster of Paris. *Discover Materials*, 5(1), 98. <https://doi.org/10.1007/s43939-025-00198-7>
68. Salih, T. W. M. (2016). Insulation materials: Fundamentals and applications. *Journal of Engineering and Sustainable Development*, 20(3), 10–18. <https://www.researchgate.net/publication/350905688>
69. Sackett, A. (1894). Wall Board and Plaster Board. U.S. Patent No. **520,123**, issued May 22, 1894. <https://patentimages.storage.googleapis.com/da/b1/d9/e909b90392f24a/US520123.pdf>
70. Smith, E. T. (2004). Acoustics 101: Practical guidelines. SoundRite Canada. [https://soundrite.ca/wp-content/uploads/2016/10/acoustics101v3\\_0.pdf](https://soundrite.ca/wp-content/uploads/2016/10/acoustics101v3_0.pdf)

## References

71. Shala, A. (2025, March 15). *This is the highest garbage mountain in the world*. Telegrafi. Retrieved from <https://telegrafi.com/en/This-is-the-highest-mountain-of-garbage-in-the-world/>
72. Steel Construction Institute. (2008). Acoustic detailing for steel construction (SCI P372). Way, A. G. J., & Couchman, G. H. [https://steelconstruction.info/images/a/a2/SCI\\_P372.pdf](https://steelconstruction.info/images/a/a2/SCI_P372.pdf)
73. Sonter, L. J., Ali, S. H., & Watson, J. E. M. (2018). Mining and biodiversity: Key issues and research needs in conservation science. *Proceedings of the Royal Society B: Biological Sciences*, 285(1892), 20181926. <https://doi.org/10.1098/rspb.2018.1926>
74. Steffen, W., et al. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science*, 347(6223), 1259855. <https://doi.org/10.1126/science.1259855>
75. Teesdale, L. V. (1958). Thermal insulation made of wood-base materials: Its application and use in houses. Oregon State University. <https://ir.library.oregonstate.edu/downloads/h128nj420>
76. Uris, A., Bravo, J. M., Gómez-Lozano, V., Ramírez, P., & Llinares, J. (2006). Sound insulation of double frame partitions with an internal gypsum board layer. *Applied Acoustics*, 67(9), 918–925. <https://doi.org/10.1016/j.apacoust.2005.11.006>
77. U.S. Geological Survey (USGS). (2024). Mineral Commodity Summaries: Gypsum. U.S. Department of the Interior. <https://pubs.usgs.gov/periodicals/mcs2024/mcs2024-gypsum.pdf>
78. Voiland, A. (2019, November 21). Making sense of Amazon deforestation patterns. NASA Earth Observatory. Retrieved from <https://www.earthobservatory.nasa.gov/images/145888/making-sense-of-amazon-deforestation-patterns>
79. Woolley, T. (2022). *Natural building techniques: A guide to ecological methods and materials*. White Lion Publishing. <https://books.google.com/books?id=fDhIEAAQBAJ>
80. Yang, K., Xu, Q., Townsend, T. G., Chadik, P. A., Bitton, G., & Booth, M. (2006). Hydrogen sulfide generation in simulated construction and demolition debris landfills: Impact of waste composition. *Journal of the Air & Waste Management Association*, 56(8), 1130-1138. <https://doi.org/10.1080/10473289.2006.10464544>
81. Yu, Dona (2015). *Sound advice: The development and use of early 20th century acoustical wall and ceiling materials*. Columbia University. <https://academiccommons.columbia.edu/doi/10.7916/D8J102P4>
82. Yuan, H., & Shen, L. (2011). Trend of the research on construction and demolition waste management. *Waste Management*, 31(4), 670–679. <https://doi.org/10.1016/j.wasman.2010.10.030>

## References