People's Democratic Republic of Algeria
Ministry of Higher Education and Scientific Research
Mohamed Khider University of Biskra
Faculty of Sciences and Thechnology
Department of Mechanical Engineering

Ref: .............

# THESIS

In Candidacy for the Degree of
DOCTOR IN MECHANICAL ENGINEERING
**Option**: Energetics

## TITLE

# Energy valorization of bio-waste applied to buildings in Algeria.

Presented by **Mr. Mohamed-Aymen KETHIRI**

Defended on: 06/02/2025

In front of the jury composed of:

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2024/2025

# Energy valorization of bio-waste applied to buildings in Algeria.

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Mechanical Departement

University of Biskra

A thesis submitted for the degree of

*PhD in Mechanical Engineering*

Publicly supported on the 06th February 2025

*To*

*My beloved family*
*Parents, siblings*
*Brothers, little sister*
*and my lovely future wife*
*My Professors*
*and my friends.*

# Acknowledgements

***"In the name of Allah, the Most Gracious and the Most Merciful"***

**Allah Almighty said : [31:12] "*Be grateful to Allah, for whoever is grateful, it is only for their own good*"**

I would like to praise *Allah* the Almighty, the Most Gracious, and the Most Merciful for His blessing In the completion of this thesis. Then, may Allah's blessing goes to His final Prophet *Muhammad* (peace be up on him), his family and his companions.

The writer wishes to acknowledge his deepest gratitude for all generous guidance and assistance which has given to him by a lot of people.

I would like to express my greatest gratitude and appreciation to my supervisor Prof.Noureddine Belghar, who has given me his valuable guidance, advice and understanding so I could complete this thesis. Most importantly, of the confidence he gave us to work independently.

Great thanks and appreciation the writer give to the jury members, Prof. Noureddine Moummi for doing me the honor of chairing the jury, Prof. Kamel Talbi and Prof. Adel Benchabane, as the examiners who had given suggestions, criticism, improvements, and valuable inputs for the thesis. Special thanks goes to Prof. Mourad Chikhi and Prof. Kamel Aoues for their encouragement and countless moments of support and help.

In addition, my greatest gratitude and appreciation are addressed to all my teachers, who gave me his valuable guidance, advice and encouragement throughout my academic years. Furthermore, I also express my deepest gratitude to Prof. Cristina Tedeschi, who has given me the chance to visit his laboratory in Politecnico di Milano and for accepting to support my research and offering scientific colaboration.

My ultimate thanks is dedicated to my beloved Mother, Leila Noudar Amraoui, my beloved Father, Nabil, for their endless support, love, and prayer. my special thanks go to my brothers Wassim, Yousri, Razind, my sister Rined and my lovely wife who have given me plentiful help and support in completing this thesis. Also, huge thanks go to all my friends for every single moment we cherished together since the first day up to this very second.

**Mohamed-Aymen Kethiri**

# Title : Energy valorization of bio-waste applied to buildings in Algeria.

**Abstract:**

In the pursuit of sustainable and environmentally friendly practices, effective biowaste management has become a crucial imperative, especially in the context of the built environment. In the context of growing global trends related to energy security, environmental degradation and climate change. Through a multidisciplinary perspective, this thesis seeks to bridge the fields of waste management, materials science, renewable energy or renewable materials and sustainable architecture, providing a holistic perspective on the exploitation of biowaste for the benefit of the Algerian community and the planet at large. The potential of using date palm leaflet (DPL) as a green composite reinforcement in construction materials. An experimental study was conducted to understand the main characteristics of DPL. The work was divided into two main axes, (i) a physicochemical characterization of date palm waste (ii) a mechanical and thermophysical characterization on a composite reinforced with date palm waste (gypsum/date palm). A series of analyses were performed, such as scanning electron microscopy (SEM) and Brunauer-Emmett-Teller (BET) analysis, to evaluate the physical properties of the fibers, including apparent and absolute densities, specific porosity and detailed morphological characteristics. In addition, the chemical composition of these fibers was meticulously examined by energy dispersive spectroscopy (EDS), X-ray diffraction (XRD) and Fourier transform infrared spectroscopy (FTIR). The thermal properties were characterized by thermogravimetric analysis (TGA). The second part of the research work focuses on the study of the impact of date palm leaflet powder (DPL) on the thermal and physico-mechanical properties of gypsum mortars. A series of mortar compositions were prepared with different proportions of DPL (0, 1, 3 and 5% w/w binder) and different particle sizes (0.5, 1 and 1.5 mm). This study provides valuable information on the use of sustainable and renewable building materials, highlighting the benefits of exploiting agricultural waste in the construction sector. The results lay the foundation for future research and innovations in the field of environmentally friendly construction technologies. This study advocates and promotes the use and valorization of date palm waste in building materials for building applications in Algeria.

**Keywords :**

Date palm; Building material; Bio-composite; Bio-Waste; Physical; Mechanical; Chemical; Thermal; Characterization; Valorization; Algeria.

# Titre : Valorisation énergétique des biodéchets appliquée aux bâtiments en Algérie.

**Résumé :**

Dans la poursuite de pratiques durables et respectueuses de l'environnement, la gestion efficace des biodéchets est devenue un impératif crucial, en particulier dans le contexte de l'environnement bâti. Dans le contexte des tendances mondiales croissantes liées à la sécurité énergétique, à la dégradation de l'environnement et au changement climatique. À travers une perspective multidisciplinaire, cette thèse cherche à relier les domaines de la gestion des déchets, de la science des matériaux, des énergies renouvelables ou des matériaux renouvelables et de l'architecture durable, en offrant une perspective holistique sur l'exploitation des biodéchets au profit de la communauté algérienne et de la planète en général. Le potentiel de l'utilisation de la foliole de palmier dattier (DPL) comme renfort composite vert dans les matériaux de construction. Une étude expérimentale a été menée pour comprendre les principales caractéristiques de la DPL. Le travail a été divisé en deux axes principaux, (i) une caractérisation physico-chimique des déchets de palmier dattier (ii) une caractérisation mécanique et thermos-physique sur un composite renforcé de déchets de palmier dattier (gypse/palmier dattier). Français Une série d'analyses ont été réalisées, telles que la microscopie électronique à balayage (MEB) et l'analyse Brunauer-Emmett-Teller (BET), pour évaluer les propriétés physiques des fibres, notamment les densités apparentes et absolues, la porosité spécifique et les caractéristiques morphologiques détaillées. De plus, la composition chimique de ces fibres a été méticuleusement examinée par spectroscopie dispersive en énergie (EDS), diffraction des rayons X (DRX) et spectroscopie infrarouge à transformée de Fourier (FTIR). Les propriétés thermiques ont été caractérisées par analyse thermogravimétrique (ATG). La deuxième partie du travail de recherche porte sur l'étude de l'impact de la poudre de folioles de palmier dattier (DPL) sur les propriétés thermiques et physico-mécaniques des mortiers de plâtre. Une série de compositions de mortier ont été préparées avec différentes proportions de DPL (0, 1, 3 et 5 % p/p de liant) et différentes granulométries (0,5, 1 et 1,5 mm). Cette étude fournit des informations précieuses sur l'utilisation de matériaux de construction durables et renouvelables, en soulignant les avantages de l'exploitation des déchets agricoles dans le secteur de la construction. Les résultats jettent les bases de futures recherches et innovations dans le domaine des technologies de construction respectueuses de l'environnement. Cette étude préconise et promeut l'utilisation et la valorisation des déchets de palmiers dattiers dans les matériaux de construction pour les applications du bâtiment en Algérie.

**Mots clés :**

Palmier dattier; Matériau de construction; Bio-composite; Bio-déchet; Physique; Mécanique; Chimique; Thermique; Caractérisation; Valorisation; Algérie.

# العنوان: التثمين الطاقوي للنفايات الحيوية في المباني في الجزائر.

**الملخص:**

في السعي لتحقيق ممارسات مستدامة وصديقة للبيئة، أصبحت الإدارة الفعالة للنفايات الحيوية ضرورة حاسمة، لا سيما في سياق البيئة المبنية. وعلى خلفية الاتجاهات العالمية المتنامية المتعلقة بأمن الطاقة والتدهور البيئي وتغير المناخ. من خلال منظور متعدد التخصصات، تسعى هذه الأطروحة إلى سد مجالات إدارة النفايات، وعلوم المواد، والطاقة المتجددة أو المواد المتجددة، والهندسة المعمارية المستدامة، وتوفير منظور شمولي حول استغلال النفايات الحيوية لصالح المجتمع الجزائري والكوكب بشكل عام. إمكانية استخدام جريد النخيل (DPL) كمقويات مركبة خضراء في مواد البناء. تم إجراء دراسة تجريبية لفهم الخصائص الرئيسية لـ DPL. تم تقسيم العمل إلى محورين رئيسيين، (1) التوصيف الفيزيائي والكيميائي لمخلفات نخيل التمر (2) التوصيف الميكانيكي والحراري الفيزيائي على مركب مقوى بمخلفات نخيل التمر (الجبس / نخيل التمر). تم إجراء سلسلة من التحليلات، مثل المجهر الإلكتروني الماسح (SEM) وتحليل Brunauer-Emmett-Teller (BET)، لتقييم الخواص الفيزيائية للألياف، بما في ذلك الكثافة السائبة والمطلقة، والمسامية المحددة والخصائص المورفولوجية التفصيلية. علاوة على ذلك، تم فحص التركيب الكيميائي لهذه الألياف بدقة بواسطة التحليل الطيفي لتشتت الطاقة (EDS)، وحيود الأشعة السينية (XRD)، ومطيافية تحويل فورييه للأشعة تحت الحمراء (FTIR). تم تشخيص الخواص الحرارية عن طريق التحليل الوزني الحراري (TGA). الجزء الثاني من العمل البحثي يتعلق بدراسة تأثير مسحوق وريقات نخيل التمر (DPL) على الخواص الحرارية والفيزيائية والميكانيكية لملاط الجبس. تم تحضير سلسلة من تركيبات الملاط بنسب مختلفة من DPL (0، 1، 3 و 5٪ وزن / وزن مادة رابطة) وأحجام جسيمات مختلفة (0.5، 1 و 1.5 مم). توفر هذه الدراسة رؤى قيمة حول استخدام مواد البناء المستدامة والمتجددة، مع تسليط الضوء على فوائد تسخير النفايات الزراعية في قطاع البناء. وتضع النتائج الأساس للبحث والابتكار المستقبلي في مجال تقنيات البناء الصديقة للبيئة. توصي هذه الدراسة وتشجع على استخدام وتثمين مخلفات النخيل في مواد البناء لتطبيقات البناء في الجزائر.

**الكلمات المفتاحية :**

نخيل التمر؛ مواد البناء الحيوية؛ النفايات الحيوية؛ فيزيائي؛ ميكانيكي؛ كيميائي؛ الحرارية التوصيلية؛ تثمين؛ الجزائر.

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# Nomenclature

**Abbreviations**

| | |
|---|---|
| MENA | Middle East and North Africa |
| TWh | Terawatt-hours |
| DP | Date Palm |
| DPF | Date palm Fiber |
| FAO | Food and Agriculture Organization |
| DPL | Date palm leaflet |
| MIP | Mercury Intrusion Porosimeter |
| BET | Brunauer-Emmett and Teller |
| SEM | Scanning electron microscopy |
| EDS | Energy dispersive spectroscopy |
| XRD | X-ray diffraction |
| FTIR | Fourier transform infrared spectroscopy |
| TGA | Thermo-gravimetric analysis |
| DN | Deglat Noor |
| MD | Mch Deglat |
| B | Bouchagroune |
| M | Mekhadema |
| L | Lichana |

# Chapter 1

# General Introduction

### Summary



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## 1.1 Introduction

In the pursuit of sustainable and environmentally friendly practices, effective management of bio-waste has become a crucial imperative, particularly in the context of the built environment. This doctoral thesis is in the field of "**Energy Recovery of Bio-waste Applied to Buildings in Algeria.**" In the context of growing global trends related to energy security, environmental degradation and climate change, this research strives to discover innovative solutions in the unique socio-economic and environmental context of Algeria.

By exploring the symbiotic relationship between bio-waste and building energy systems, this study aspires to provide valuable insights and strategies that transcend conventional paradigms, fostering a more resilient and sustainable future for both the Algerian built environment and for the broader area of renewable energy use. Through a multidisciplinary perspective, this thesis seeks to connect the fields of waste management, materials science, renewable energy or renewable materials and sustainable architecture, providing a comprehensive perspective on the exploitation of energy latent bio-waste for the benefit of Algerian communities and the planet at large.

## 1.2 Problematic

In the modern era, the accelerated growth of human activity is accompanied by an important consequence: the rapid accumulation of waste. This waste stream, which includes a wide range of materials from household waste to industrial by-products, poses an enormous challenge to the health and well-being of our planet. The scale of this problem is staggering according to the World Bank: global waste production is expected to reach 3.4 billion tonnes by 2050, up from 2.01 billion tonnes in 2016. Internationally, the dominant waste category is food and green waste, which constitutes 44 % of waste generated. Additionally, dry recyclables, including plastic, paper, cardboard, metal and glass, collectively account for an additional 38% of the total waste generated, see the figure 1.1 [1].

Faced with a booming global population and increasing consumption patterns, the accumulation of food and green waste from various sources, has become an urgent environmental concern. By focusing on the Middle East and North Africa (MENA) region, it is noted that 58% of this waste is food and green, see the figure 1.2. This growing stream of waste, including plant waste, bio-waste and municipal organic waste, poses a significant threat to the health and well-being of our planet [2, 3, 4]. The increase of organic waste derived from vegetables globally stands as a significant factor contributing to the occurrence of forest fires, subsequently leading to the emission of $CO_2$.

Recent data reveals that the accumulation of waste from date palms in the MENA region represents a notable bio-resource that is largely underutilized [5]. The effective management of date palm waste poses a notable challenge in the MENA region, as highlighted in previous research [6]. A key obstacle lies in determining the optimal methods for the disposal of this substantial volume of renewable resources. Recent research findings from Awad et al. [6] and Mohamed, Saba, and Alothman [7] demonstrate that the global population of date palms has surpassed 120 million trees, predominantly concentrated in the MENA [8, 9]. Each of these enduring trees boasts a lifespan exceeding 100 years, yielding fruits and by-products annually. The date palm, a member of the Phoenix dactylifera L. family, holds significant importance as a fruit-bearing tree in Algeria, where the population exceeds 20 million palms [10, 11]. This considerable number of trees makes Algeria the largest country in Africa and the fourth largest date producer in

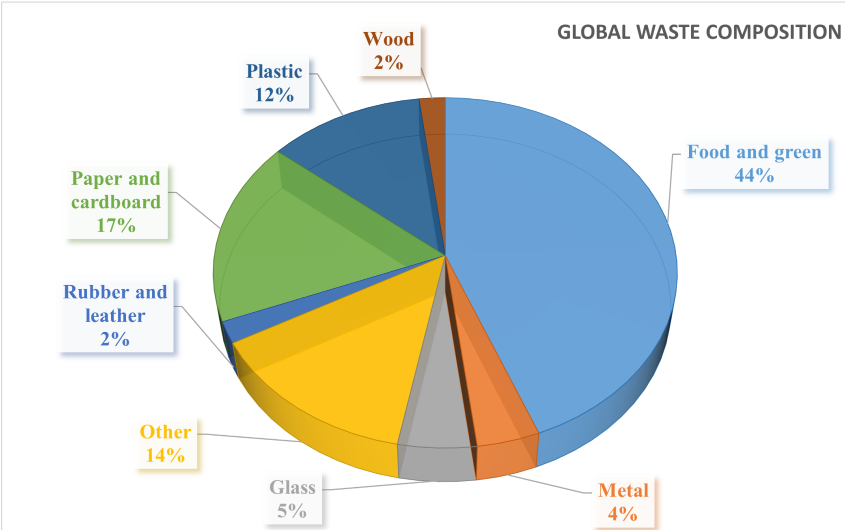


**Figure 1.1:** Global waste composition.

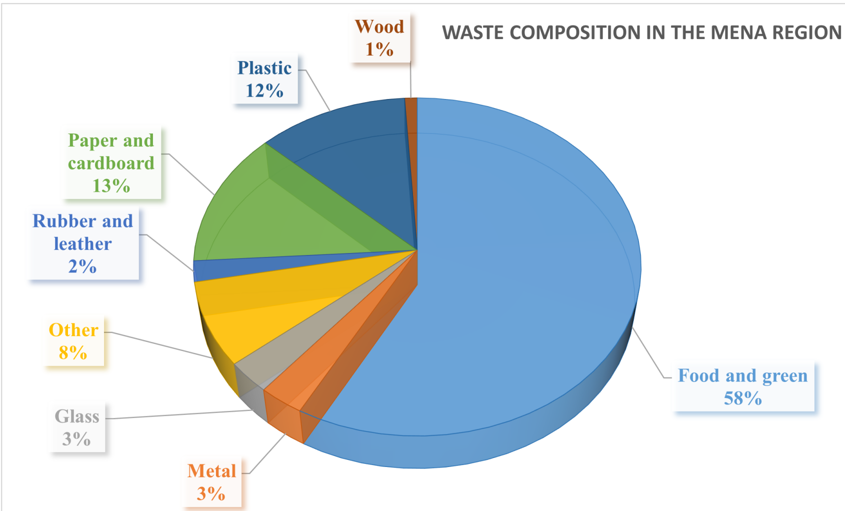


**Figure 1.2:** Waste Composition in the MENA region.

the world, with about 1.1 million tons per year. Furthermore, there are over 2,600 species of palm trees [7] and approximately 1,000 species of Algerian palms, including soft, dry, and semi-dry varieties, which are adeptly adapted to various soil and climatic conditions [12]. Studies have proven and explained that each palm can yield between 40 and 50 kg of palm waste per tree annually [7, 13]. Therefore, these different parts generate significant waste, amounting to more than 800,000 tons per year in Algeria only [14, 15].

The report also highlights the environmental, social, and economic challenges associated with this increase in waste. It highlights the need for effective waste management, including recycling and source reduction, to reduce negative impacts on the environment and human health. Sustainable waste management is seen as crucial to achieving the targets.

The degree of danger associated with the spread of waste around the world requires urgent attention and comprehensive solutions. As we grapple with the effects of rampant consumption and poor waste management, the need to address the multifaceted problems posed by the accumulation of hazardous waste has become imperative [16]. This act sets for a critical examination of the challenges facing waste accumulation, exploring its impact on ecosystems, human health, and the overall sustainability of our planet [17]. Through a focused lens, we delve deeper into the complexities surrounding waste risks, with the aim of revealing the complexities of this global situation and advocating for strategies that pave the way for a more sustainable and harmonious coexistence with our environment [16].

## 1.3 Challenge Taken-up

This work addresses major challenges: (i) solving the global problem, particularly in Algeria, of the accumulation of biowaste through an innovative approach. (ii) Valorizing biowaste by using it as a reinforcing agent in building materials to improve their thermal properties and make them insulating. (iii) Reducing $CO_2$ emissions during the production of building materials (cement, gypsum, etc.) and also during energy production. This effort not only addresses waste management issues, but also opens a new trajectory in sustainable construction methodologies.

The valorize of biowaste by using it to reinforce building materials, enhancing their thermal insulation properties. By integrating biowaste into materials like bricks and concrete, energy demands for heating and cooling can be reduced, which is particularly beneficial for Algeria's extreme climate. This approach supports sustainability and energy efficiency goals while reducing reliance on traditional, costly insulation materials and promoting a circular economy model.

A key focus of this research is to reduce $CO_2$ emissions in building material production and energy generation, as construction is a major source of global greenhouse gas emissions. Using biowaste-based components can lower the carbon footprint of materials like cement, and improved insulation from biowaste reduces building energy needs, further cutting emissions. For Algeria, this aligns with climate commitments and sustainability goals, showcasing a proactive approach to mitigating climate change in the construction sector.

The trend of primary energy consumption from 2002 to 2022, measured in terawatt-hours (TWh), was shown in Figure 1.3. Upon observing the data, a clear and consistent upward trajectory in energy consumption was noted over these years. Starting at slightly over 300 TWh in 2002, consumption was found to have steadily risen, reaching approximately 750 TWh by 2022. This consistent increase was indicative of a significant growth in energy demand over the two decades, nearly doubling during this period.

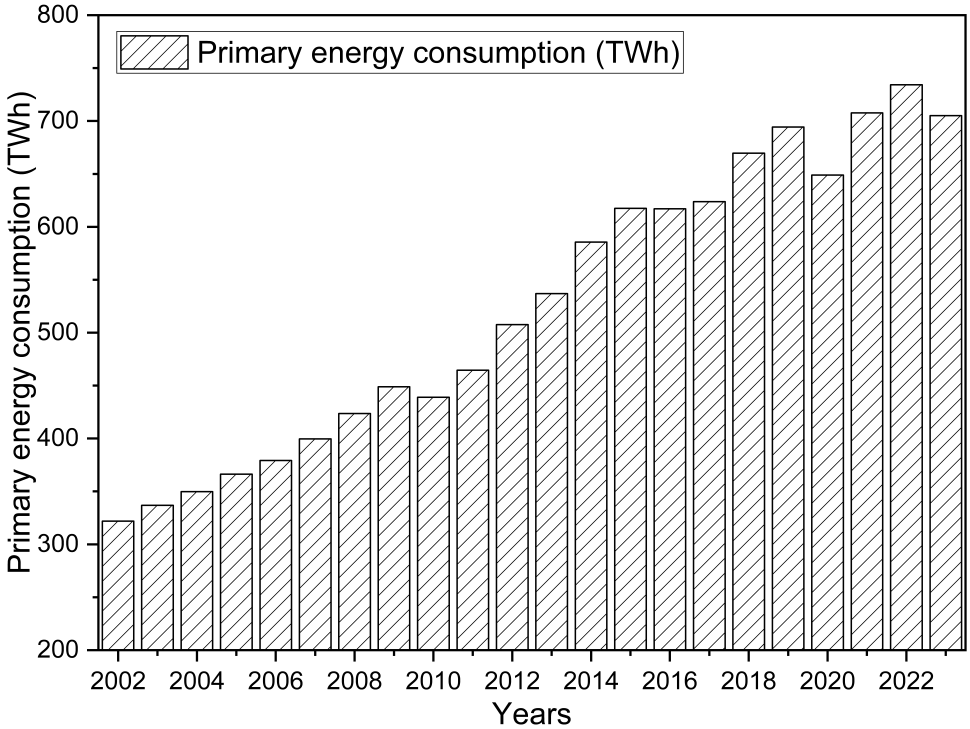


**Figure 1.3:** Domestic electricity consumption in Algeria.

Such a high and growing rate of energy consumption presents substantial challenges. Meeting this ever-increasing demand places a strain on energy resources, which are often finite and environmentally impactful. Additionally, reducing energy consumption in the face of such a trend is difficult, as it requires systemic changes in consumption habits, energy efficiency practices, and potentially costly infrastructure adjustments. Addressing this issue will require significant innovation, investment, and policy changes to transition to a more sustainable and efficient energy consumption model.

## 1.4 Potential and Possibility of studying

Exploring the use of biowaste in construction materials is attracting considerable attention in the field of sustainable development [3]. Research indicates that various forms of biomass waste, including agricultural residues and forestry by-products, are being studied for their potential use in creating low-carbon products. This transition to the use of biomass aligns with global efforts to reduce $CO2$ emissions and mitigate environmental impacts associated with traditional waste disposal methods, such as unregulated land disposal and burning, which contributes to greenhouse gas emissions and other environmental problems.

In developed countries, the focus has been on re-utilizing biomass waste for energy and heat production. For example, in the European Union, wood pellets made from sawdust are a popular source of energy and heat [18]. Meanwhile, in the USA, a shift from traditional waste management practices like burning or landfilling agricultural residues has led to these materials being used more productively in industry [19, 20]. This trend is reflected in the increasing use of agricultural residues like corn stover and wheat straw for energy production. The potential of biowaste as a reinforcement in construction materials represents a significant opportunity to address the challenges of waste management and sustainable development simultaneously. It's a promising area of research that could lead to innovative solutions in the construction industry, aligning with global sustainability goals [21].

Many studies have been conducted to investigate the potential possibility to employ plant wastes or natural fibre in building material as reinforcement fibers for enhanced structural performance [22, 23]; as date palm wood and fibre has long been an exploitable source of building materials [24, 25, 26, 27, 28, 29]. These studies have shown promising results, indicating that utilizing plant-based natural fibers in building materials can improve their strength and durability. Furthermore, the use of plant-based natural fibers can also contribute to sustainability efforts by reducing reliance on synthetic materials and promoting the utilization of renewable resources. Overall, the research suggests that incorporating plant-based natural fibers in building materials has the potential to enhance structural performance, promote sustainability, and reduce reliance on synthetic materials [30, 31]. Over the past two decades, researchers have focused on exploiting palm waste in construction materials. The figure 1.4 shows that the number of researches is increasing and that this number is also increasing over time.

### 1.4.1 Potential and Possibility of studying in Algeria

In a world where environmental and economic issues were increasingly pressing, it was deemed essential that scientific research and public policies be aligned to address major challenges, such as waste management and exploitation. Waste was recognized as an underexploited resource while being seen as offering considerable potential for sustainable development and the circular economy.

In Algeria, the country stood out for its scientific wealth in the field, with 29% of its research publications focused on utilizing date palm waste and building materials 1.5. This was seen as evidence not only of national expertise but also of the ability to innovate and propose solutions tailored to both local and global needs. Algeria possessed the necessary resources-raw materials, proven techniques, and solid scientific advancements. Yet, these assets remained largely underutilized due to a lack of clear commitment and coordinated

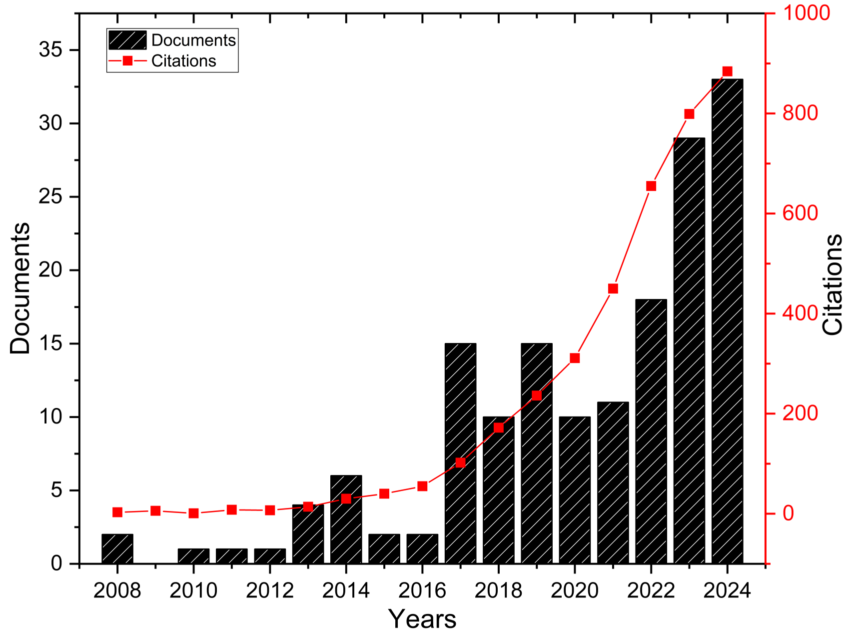


**Figure 1.4:** Number of documents and citations according to Scopus database for 'date AND palm AND building AND material' keywords.

strategy. To address this, researchers, policymakers, and industrial stakeholders were urged to unite and focus on key actions:

1. **Strengthen investments in research and development**: Initiatives aimed at transforming waste into valuable resources-whether energy, materials, or innovative productsâĂŤneeded to be supported and prioritized.

2. **Promote technological innovation**: Modern and accessible techniques for optimizing waste recovery were to be adopted and widely disseminated.

3. **Develop supportive public policies**: Legislative and financial frameworks were required to incentivize companies to integrate waste recovery solutions into their operations.

4. **Raise awareness and educate**: Public engagement was critical, with citizens encouraged to recognize the environmental and economic benefits of waste recovery.

The challenge was significant, but so too were the opportunities. It was believed that by taking decisive action, Algeria could transform a problem into a valuable resource and turn obstacles into opportunities. The country was seen as having everything necessary to become a leader in this field, setting a benchmark for the region and the world. Stakeholders were urged not to let this opportunity slip away, but instead to work collectively toward building a sustainable and prosperous future for all.

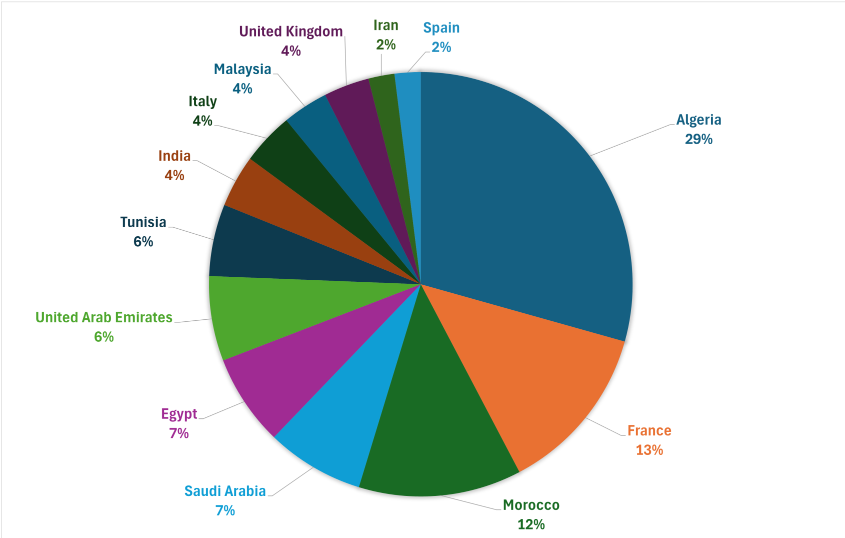


**Figure 1.5:** Percentage contribution in scientific publications according to Scopus database for 'date AND palm AND building AND material' by country.

## 1.5 Research objectives

The primary ambition of this thesis is extending beyond mere academic inquiry; it seeks to harness the potential of date palm biowaste, an abundant yet underutilized resource in Algeria, transforming it into a cornerstone for the development of advanced building materials. This exploration aims not only to improve the performance characteristics of these materials, but also to integrate sustainability and energy efficiency into the very fabric of construction practices. In doing so, the research aims to make a substantial contribution to the realization of a circular economy in Algeria, a model that emphasizes waste reduction and continuous use of resources.

This work motivated by the dual objective of environmental management and economic innovation. It recognizes the critical need for sustainable development strategies in the construction sector, which currently faces challenges related to resource depletion, waste management and environmental degradation. Thanks to the innovative application of date palm biowaste in construction materials, this study offers a new way to address these challenges. It aims to demonstrate how this approach can not only mitigate the environmental impact associated with traditional building practices, but also improve the thermal, mechanical and durability properties of building materials, thereby contributing to more energy efficient and resilient structures.

Furthermore, this research fits into the broader context of the MENA region and highlights Algeria's commitment to sustainable development and green economy principles. By exploring the potential of date palm biowaste as a resource for energy recovery and material valorization, the thesis aligns with national and international efforts to promote resource efficiency, waste reduction and environmental sustainability. It aims to provide actionable insights and scalable solutions that can be adopted by policymakers, industry stakeholders and the scientific community to foster a more sustainable construction sector in Algeria and potentially similar semi-arid regions.

In summary, the overarching aim of this thesis transcends the mere academic exploration of biowaste utilization; it aspires to drive a change in basic assumptions in the construction sector towards more sustainable and circular practices. Through this research, date palm biowaste is considered not as an end-of-life product but as a valuable resource that can contribute significantly to the development of sustainable, efficient, and innovative construction materials, marking a step forward in Algeria's path towards sustainable development and circular economy.

The co-occurrence network visualization of the keywords for the 167 relevant articles was shown in Figure 1.6. The size of the label and the circle around each keyword was determined by its weight, with the circle increasing in size as the keyword weight increased. For instance, the keyword corrosion was found to have the largest label and circle size due to its highest number of occurrences.

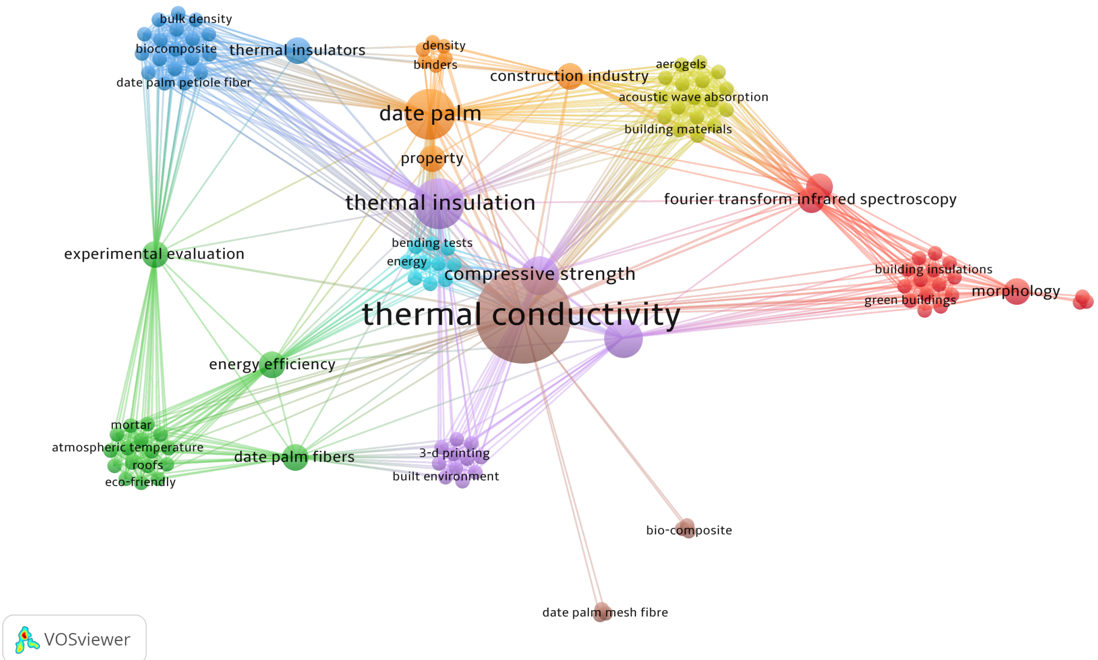


**Figure 1.6:** Co-occurrence network visualization of keywords for the 167 relevant articles.

## 1.6 Work methodology

To guarantee a credible and methodical investigation, we have adopted a structured working methodology. This approach is essential for in-depth examination of a material's attributes and its potential applicability in specialized fields such as materials science, engineering, and environmental research. The organization and execution of the thesis are guided by this overall methodology, ensuring a systematic exploration of the subject.

Additionally, the thesis is strategically segmented into five chapters, each designed to build on the knowledge gained in previous sections, thereby providing a coherent and comprehensive understanding of the subject. This structure facilitates a logical progression of ideas and findings, essential for building foundations, conducting research, and drawing meaningful conclusions. Below is an overview of the chapters that make up the thesis:

Chapter 1 "**Introduction**": summarizes the problem the research aims to solve, highlights challenges present in the current body of knowledge or technology, describes the objectives of the research, and briefly describes the methodology to be used.

Chapter 2 "**Literature Review**": provides a comprehensive review of the literature, discussing existing research and findings relevant to the topic of the thesis to establish the current state of knowledge and identify gaps that the research aims to fill .

Chapter 3 "**Materials and Methods**": details the preparation methods of the materials used in the study, describes the experimental and testing methods, and describes the standards and protocols followed in the research process.

Chapter 4 "**Results and Discussion**": presents the research findings, including data and analyses, and then discusses these findings, providing interpretations, comparisons with existing literature, and implications of the findings.

Chapter 5 "**Recommandation and Conclusion**": summarizes the main findings and their significance, offers practical or theoretical recommendations based on these findings, and suggests potential areas for future research to further explore or build on the study findings.

This structured approach not only ensures the completeness of the thesis, but also facilitates a rich understanding of the research topic, providing clarity and insight into the methodology, analysis, and conclusions. By adopting this methodology, the thesis aims to contribute significant and impactful knowledge to the field, highlighted by a rigorous and systematic examination of the subject.

## 1.7 Conclusion

In conclusion, this chapter introduced the problem of the accumulation of biowaste and its potential environmental, social, and economic impacts. This thesis will respond to this challenge by studying the energy recovery potential of biowaste applied to buildings in Algeria.

This chapter: begins with an introduction highlighting the global importance of waste management, then explores the specific challenges Algeria faces regarding the accumulation of biowaste in the built environment. Ends with a description of the research objectives intended to respond to these challenges, emphasizing the objective of contributing both academically and practically to the development of sustainable solutions adapted to the Algerian context. The following chapters will delve into the intricacies of biowaste-to-energy technologies, assessing their feasibility and potential impact on construction practices, with the overarching goal of fostering a more resilient and environmentally friendly built environment in Algeria.

# Chapter 2

# Literature Review

### Summary



## 2.1 Introduction

This chapter aims to synthesize and critically analyse the existing body of knowledge, understand gaps, challenges, and opportunities in the application of bio-waste-to-energy systems within the built environment. By elucidating the theoretical frameworks, methodological approaches, and empirical findings in relevant literature, it seeks to lay a robust foundation for the subsequent chapters, guiding the exploration of energetical recovery strategies tailored to the Algerian context. Through this comprehensive literature review, we endeavour to contribute valuable insights that inform the development of sustainable, context-specific solutions for the integration of bio-waste recovery technologies in the construction sector of Algeria.

## 2.2 Date Palm Tree

The date palm, with origins tracing back to 4000 B.C. in Mesopotamia, thrives in North Africa, the Arab Peninsula, and Iran [32]. This species has a long history and a high renewability rate. Date Palm trees (**Phoenix dactylifera L.**) are the largest Phoenix class, with heights reaching above 30 m and date fruit bunch sizes of up to (10 * 40 mm), as the figure 2.1 show.

**Figure 2.1:** Date palm tree (Phoenix dactylifera L.)

Date Palm (DP) tree has many branches formed at its trunk base; the DP can live up to 100 years and over [7]. Persistent grayish leaf bases cover DP tree trunk. Its leaves are long and have pinnate shape with a good arrangement and its fronds are needle sharp. Every year, 10 to 20 new leaves are grown. The bases of DP leaves are surrounded by a strong fibrous sheath [33]. Other study, said that the average, 13 leaves, 13 petioles and

7 bunches are cut per date palm in the annual pruning process [14]. These trees have special characteristics that allow them to grow under various conditions, such as deserts and hot environments [34]. Date palm Fiber (DPF) can be extracted from different parts of the tree such as trunk, leaves, fronds, fruit bunch, and sheath [35].

These components have been traditionally used in a variety of applications: midribs in construction and crate manufacturing; leaflets for making mats, baskets, and bags; coir in crafting ropes and brooms; spadix stems for brooms and sieves; and trunks as construction materials and furniture [7]. This rich heritage showcases the diverse and traditional uses of date palm by-products in the Arab region, highlighting their preparation and geometrical characteristics. as the figure 2.2 show.

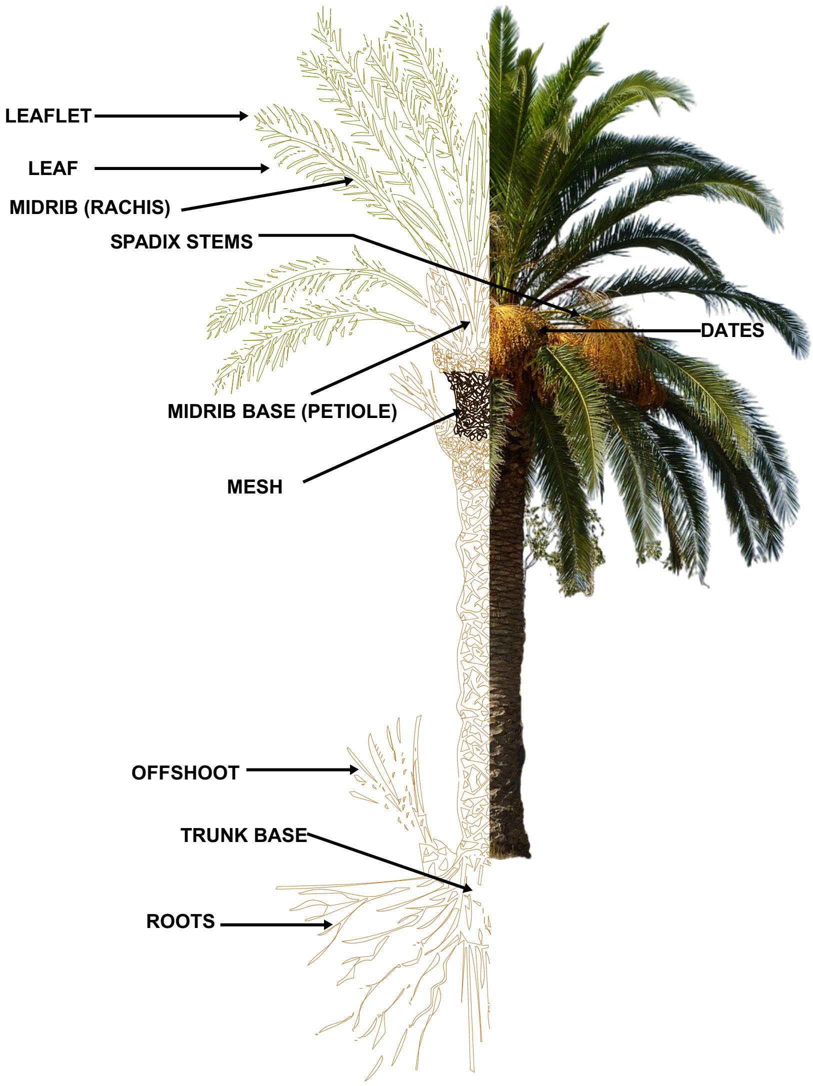


**Figure 2.2:** Date palm tree parts.

## 2.3 Date Palm statistic

Date palm is a flowering plant from the palm family, and it is widely cultivated in the MENA [6]. The date palm tree can grow in desert environments, characterized by scarcity of rainfall, water shortage, and extreme temperatures [25, 36].

In 2009 Alawar, said that there are more than 100 million date palm trees in the world and each tree can grow for more than 100 years [8] this information was based on statistics was do it in 1999. In 2010, El-Juhany estimated that there is 120 million date palms in the world and over two-thirds are in MENA region [25], this number was confirmed in some recent research such as [6, 7, 34, 37, 38]. However Agoudjil in 2011, mentions that there are approximately 105 million palm trees covering an area of 800,000 ha based on the statistics of Food and Agriculture Organization in 2006 and it was confirmed by Jonoobi in his review about the date palm tree [5]. In 2021, Elseify says the global population of is estimated at 140 million date palms [39].

In 2006, world production of dates was about 7 million tons and the top 10 producing countries were Egypt, Saudi Arabia, Iran, United Arab Emirates, Pakistan, Algeria, Sudan, Oman, Libya, and Tunisia [40]. In 2020, a scientific study conducted and cited within the article revealed that worldwide date production has reached a total of 8.7 million tons where the major production came from Egypt, Saudi Arabia, Iran, and Algeria [41]. This significant figure highlights the global scale and importance of date cultivation, underscoring its vital role in the agricultural sector and its impact on food supply chains around the world.

Contrary to the figures cited in various scientific publications, the Food and Agriculture Organization (FAO) of the United Nations reported in 2023 [42] (Food and Agriculture Organization of the United Nations 2023) a more extensive utilization of land for date palm cultivation, amounting to 960,611 hectares globally. This substantial acreage yielded an impressive production total of 8.4 million tonnes of dates, as table 2.1 shows. This declaration by the FAO underscores the significant scale and impact of date palm cultivation worldwide, reflecting its vital role in the agricultural sector and its contribution to global food supplies.

### 2.3.1 Statistics on date palm in Algeria

In Algeria, the valorization and study of this type of waste 'Date palm waste' were initiated in 2004 by Kriker et al. [109]. The University of Biskra was also involved in the development of this subject from 2010 by Prof. Adel et al. [14], and was later followed by several doctoral theses and scientifics papers that had the opportunity to contribute

**Table 2.1:** Dates productions and area harvested statistics.

| Countries | Productions (tones) | Countries | Area harvested (ha) |
|---|---|---|---|
| Egypt | 1733432,48 | Iraq | 278159 |
| Saudi Arabia | 1610731 | Algeria | 176044 |
| Algeria | 1247403,75 | Saudi Arabia | 156460 |
| Iran | 1030459,72 | Iran | 122332 |
| Iraq | 715293,32 | Tunisia | 77805 |
| United Arab Emirates | 397328,94 | Morocco | 65432 |
| Oman | 376980 | Egypt | 58557 |
| Tunisia | 369000 | United Arab Emirates | 40739 |
| Libya | 187870,08 | Libya | 34644 |
| Morocco | 137393,77 | Oman | 26355 |

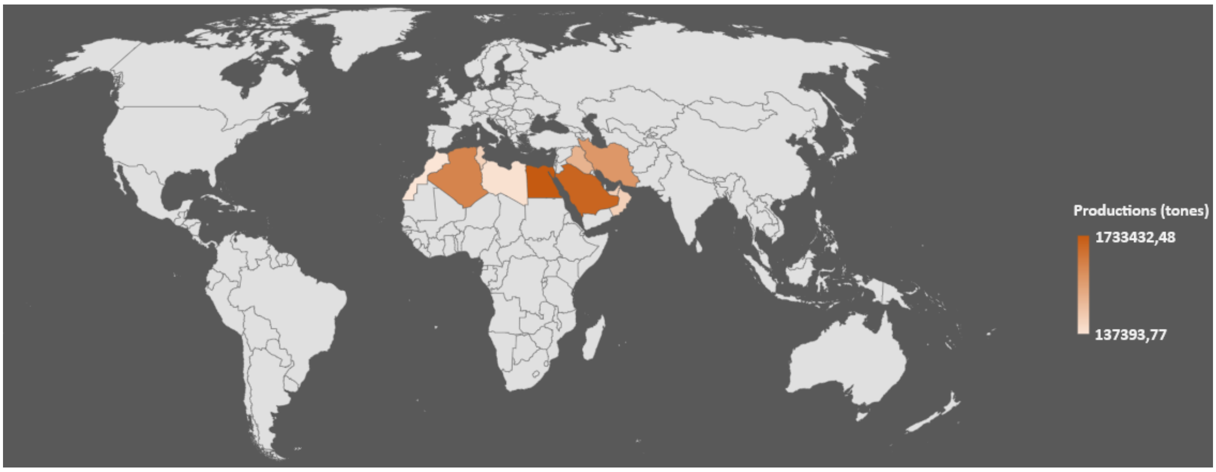


**Figure 2.3:** Dates production by country.

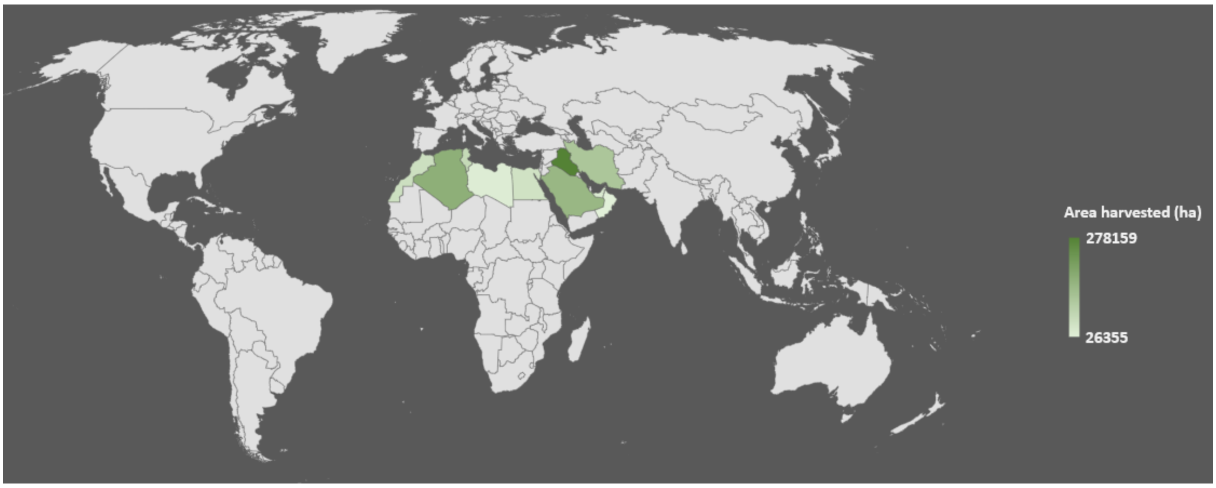


**Figure 2.4:** Dates harvest area by country.

to this development. From the beginning, the objective was set to develop innovative solutions to improve energy efficiency, enhance the characteristics of materials, and reduce the environmental impact of this waste. These studies not only led to significant scientific advances but also opened up promising perspectives in terms of impact.

In 2010, El-Juhany in his work mention that Algeria contains 10.47 million of date palm tree with a production of 500.000 tons per year [25]. Under the auspices of the country's agricultural policy, which steadfast ly supports this particular crop, farmers are being actively encouraged to cultivate palm trees. This strategic initiative is designed not only to bolster local agriculture but also to leverage the economic and environmental potential of palm cultivation, aiming for a sustainable and profitable future in the sector. According to the direction of the agricultural services of Biskra region (Algeria), the number of palm trees exceeds 15 million in Algeria, last decade, reported by Almi [13].

Sevral studies highlight that Algeria has experienced a significant surge in date palm cultivation, with an impressive increase of 18 million trees [43, 44]. This exceptional expansion emphasizes the nation's resolute commitment to broadening its agricultural horizons and fortifying its standing within the international date palm industry. By achieving a milestone of 20 million date palms [45, 46], the country not only showcases its agricultural prowess but also sets a new benchmark in the global market, signaling its potential as a leading date palm producer.

Recent data underscores Algeria's position as a leading force among the world's top three producers and exporters of dates, as table 2.1 shows, boasting a substantial yield of 1.24 million tons harvested from 176,044 hectares. This impressive output is supported by an expansive grove of over 21.8 million date palm trees. These statistics, sourced from the FAO of the United Nations [42], highlight Algeria's pivotal role in the global date market and its significant contribution to agricultural - excellence on an international scale.

### 2.3.2 Statistics on date palms waste

Many study estimated that 1.13 million tonnes of date palm waste are produced each year worldwide [43, 47, 48]. Other studies have estimated the total annual date palm waste at approximately 1.91 million tons including over than 1 200 000 tons of petioles, 410 000 of leaves and 300 000 of bunches [14, 43, 49]. Conversely, Elseify asserts that the global production of date palm waste amounts to 4.8 million tonnes of green by-products annually [39].

Date palm tree can produce annually large number of natural fibers that can be utilized in different industries. Based on research and surveys aimed at quantifying the annual palm waste production, several regions have been examined in depth, revealing significant results such as in Saudi Arabia 35 kg [50], in Malaysia 20 kg [34, 51], in Algeria (Biskra)

47.57 kg [13], in Algeria (El-Oued located) 40 kg [10], in Iran 34 kg [52, 53], in Egypt 26 kg [6, 54] and, also in Egypt 54 kg [55].

The study conducted by Agoudjil et al. [14] and his team reveals that, on average, each date palm annually generates 13 leaves and petioles, and 7 bunches, resulting in an estimated production of approximately 210,000 tonnes of date palm petioles, 73,000 tonnes of leaves, and 52,000 tonnes of bunches in Algeria alone. This investigation has been validated and cited by several works such as [11, 43, 46, 48, 49, 56]. Another survey of farmers and agricultural organizations in the Biskra region by Almi estimated that each tree produces approximately 47.57 kg of palm residue per year. This quantity is composed of 28.7% leaflets, 27% rachis, 23.9% petioles, 6.3% fibrils, 5% spathes, 4.9% clusters, 3.3% pedicels and 0.8% thorns [13].

Therefore, estimates of the total waste from these various components vary significantly, with some studies, such as those by [11, 15] , suggesting a figure of 800,000 tonnes, while other research, like that by [57], indicates a lower estimate of 200,000 tonnes annually in Algeria alone.

**Table 2.2:** Date Palm waste statistics.

| Date palm parts | Percentage of waste (%) | | |
|---|---|---|---|
| | [14] | [13] | Present work |
| Palm midribs | - | 27 | 26.2 |
| Palm leaflets | 21.46 | 28.7 | 26.5 |
| Spadix stems | - | 5 | 5.2 |
| Petiole | 62.82 | 23.9 | 30.2 |
| Bunches | 15,52 | 4.9 | 7.1 |
| Mesh | - | 6.3 | 4.8 |

## 2.4 Date palm fibre characteristics

Many researchers from the MENA region and beyond have conducted studies on the characterization of date palm waste. These efforts aim to better understand its components and optimize its utilization in suitable applications [58, 59].

### 2.4.1 Chemical properties of DPF

Several studies focus on the chemical properties of different parts of the DP. The chemical components and properties of the DP have been analyzed using various methods. All previous research indicates that the date palm is primarily composed of cellulose, hemicellulose, and lignin, with varying concentrations depending on the specific part studied. These studies employ characterization techniques such as spectroscopy, X-ray, and infrared methods to identify the presence of cellulose, hemicellulose, and lignin. Specifically, methods like Energy Dispersive X-ray Spectroscopy (EDS/EDX), X-ray Diffraction (XRD), and Fourier Transform Infrared Spectroscopy (FTIR) [10, 11, 59, 60] have been utilized to confirm the existence of these components. Additionally, various studies have employed multiple chemical analysis techniques to determine the values and levels of cellulose, hemicellulose, and lignin in each part of the DP. The table 2.3 summarizes these quantities.

**Table 2.3:** The concentration of cellulose, hemicellulose, and lignin in date palm compartments according to previous work.

| Date palm parts | Cellulose (% wt.) | Hemicellulose (% wt.) | Lignin (% wt.) | References |
|---|---|---|---|---|
| Date palm fibre | 26.92 | 43.21 | 27.42 | [61] |
| leaflet | 39.23 | 28.41 | 20.05 | [62] |
| Midribs | 46.41 | 25.89 | - | [63] |
| Seeds | 24.75 | 25.03 | 30.55 | [64] |
| Seeds | 23.9 ±0.1 | 26.8 ±0.1 | 21.6 ±0.1 | [65] |
| Mesh | 32-35.8 | 24.4-28.1 | 26.7-28.7 | [66] |
| Mesh | 39.7-40.2 | 22.3-21.9 | 19.4-17.7 | [67] |
| Fibrillum | 50.6 ±1.3 | 8.1 ±0.3 | 31.9 ±1.3 | [68] |
| Leaflets | 29.7 ±1.3 | 23.3 ±1.2 | 11.6 ±1.3 | |
| Rachis | 39.8 ±0.9 | 31.4 ±3.2 | 14.0 ±0.9 | |
| Leaf sheath | 34.0 ±0.7 | 28.9 ±1.8 | 18.2 ±0.7 | |
| Leaf stalk | 35 | 15.4 | 20.1 | [35] |
| Bunch stalk | 44 | 26 | 11 | |
| Leaf sheath fibe | 43.50 | 24 | 18 | |
| Trunk | 40 | 9.75 | 29.5 | |
| Mesh | 43.71 | 18.66 | 29.43 | [6] |
| Rachis | 39.93 | 26.48 | 25.20 | |
| Leaflets | 40.21 | 20.05 | 25.19 | |
| Midribs | 45.66 | 25.65 | 28.85 | |
| Trunk | 36.02 | 32.45 | 25.90 | |
| Average DPF | 41.1 | 24.66 | 26.91 | |
| Petiole | 33.79 | 20.44 | 26.03 | [13] |
| Rachis | 41.42 | 19.35 | 33.00 | |
| Thorns | 35.05 | 21.17 | 30.10 | |
| Leaflets | 38.58 | 20.05 | 28.57 | |
| Bunch | 39.82 | 20.68 | 29.97 | |
| Pedicels | 33.29 | 21.15 | 27.64 | |
| Spathe | 42.48 | 19.10 | 28.27 | |
| Fibrillium | 43.94 | 21.68 | 27.80 | |

### 2.4.2 Physical Properties of DPF

The physical properties of DPF, such as density, moisture content and porosity, play a crucial role in many industrial and domestic applications. The density of a fiber, has significant implications. Low-density fibers are preferred in weight-sensitive applications like aerospace and automotive industries. They also serve as excellent thermal and acoustic insulators, trap more air, and are more comfortable and manageable in textiles.

Moisture content and porosity are crucial factors affecting fiber performance. Moisture content, the amount of water in fibers, influences their mechanical properties, with some fibers becoming stronger when wet and others becoming brittle. High humidity can promote mold and bacteria growth, reducing durability. The porosity, is vital for absorbing and retaining liquids, important for filters and absorbent fabrics. High porosity improves insulating properties and air circulation, enhancing comfort by allowing sweat to evaporate. Additionally, various studies have used several techniques and standards to determine the density, moisture and porosity in each part of the DP. Table 2.4 summarizes these properties.

### 2.4.3 Mechanical Properties of DPF

The mechanical properties of date palm fibers, particularly tensile strength and Young's modulus, are crucial to their performance and suitability in various applications. Tensile strength measures the maximum stress a material can withstand while being stretched or pulled before breaking, indicating the fiber's ability to withstand tension forces. Young's modulus, on the other hand, quantifies a material's stiffness or resistance to deformation under tension, providing insight into its structural integrity.

By incorporating DPF with desirable mechanical properties into composite materials, engineers can create lightweight yet strong structures suitable for various applications, including construction,components, and aerospace engineering. Additionally, various studies have used several techniques and standards to determine the tensile strength and young's modulus in each part of the DP. Table 2.5 summarizes these properties.

### 2.4.4 Thermal Properties of DPF

The thermal properties of DPF, such as thermal conductivity, heat capacity and heat resistance, play a crucial role in their use in various applications. The thermal properties of natural fibers, in general, largely determine their effectiveness and comfort in various applications. Understanding and optimizing these properties helps maximize the benefits of natural fibers in products ranging from textiles to building materials and beyond. In

**Table 2.4:** The physical properties of date palm waste according to previous work.

| Date palm parts | Density (Kg/m3) | Moisture (wt.%) | Porosity (%) | References |
|---|---|---|---|---|
| Mesh | 121 ±5 | - | - | [69] |
| Mesh | 121 ±3 | 387 ±2 | 88.5 ±2.4 | [70] |
| Stem fibe | 917 | - | - | [7] |
| Date palm fibe | 900-1200 | - | - | [34] |
| Date palm fibe | 600 - 700 | 5.6 | - | [71] |
| Date palm fibe | 920 | - | - | [72] |
| Date palm fibe | 1088.81 | 75 | - | [73] |
| Leaflet | 1019.7 | - | 18.5076 | [74] |
| Petioles | 190 | - | - | [75] |
| Leaflets | 710 ±38.80 | 8.33 | - | [62] |
| Seeds | 644 | - | - | [41] |
| Bunch | 341-389 | - | - | [14] |
| Petiole | 187-276 | - | - | |
| Fibrillum | 979 | 9.1 ±0.9 | - | [68] |
| Leaflet | 1011 | 5.9 ±0.7 | - | |
| Rachis | 984 | 7.5 ±1.4 | - | |
| Leaf sheath | 881 | 8.8 ±1.1 | - | |
| Petiole | 160 | 146 | 81.52 | [13] |
| Rachis | 635 | 36.88 | 15.44 | |
| Thorns | 431 | 83.85 | 39.8 | |
| Leaflets | 411 | 96.6 | 50.6 | |
| Bunch | 555 | 63.2 | 32.8 | |
| Pedicels | 425 | 73.78 | 43.25 | |
| Spathe | 328 | 130.83 | 63.43 | |
| Fibrillium | 209 | 115.11 | 73.41 | |

addition, few studies have focused on the thermal properties of DPF. Table 2.6 summarizes these studies with their results.

## 2.5 Composite materials reinforced with DPF

Several studies have been conducted to characterize date palm waste to better understand its properties. This research aims to properly valorise the waste and identify suitable matrices for its use as a reinforcement material. According to the literature, date palm waste has enormous potential to be used as reinforcement in several matrix [60]. From the results obtained from the literature, physical properties [13, 34, 71, 72, 74, 75, 76] show that palm waste can improve the lightness, porosity and water absorption of the composite.

In terms of mechanical properties [8, 73, 77, 78], the DPF can improve the flexural, compressive and flexural properties of the composite due to its tensile strength and young

**Table 2.5:** The mechanical properties of date palm waste according to previous work.

| Date palm parts | Dimension (mm) | Tensile strength (MPa) | Young's modulus (GPa) | References |
|---|---|---|---|---|
| Date palm fiber | - | 5567 | - | [71] |
| Date palm fiber | 0.11 | 275 | 8.45 | [8] |
| Date palm fiber | - | 107.36 | - | [73] |
| Date palm fiber | 0.11 | 58203 | 27.5 | [34] |
| Stem fibe | - | 60275 | 212 | [76] |
| Mesh | 0.72−0.85 | 102 ±8 | 5.5 ±0.4 | [77] |
| Petiole | 0.53−0.71 | 212 ±2 | 8.9 ±0.8 | |
| Rachis | 0.42−0.58 | 388 ±8 | 20.4 ±1.2 | |
| Bunch | 0.14−0.19 | 545 ±11 | 5.0 ±1.5 | |
| Petiole | 0.4−1 | 90 | 7 | [13] |
| Rachis | 0.6−0.75 | 213 | 8.5 | |
| Thorns | 0.7−0.73 | 95.35 | 3.87 | |
| Leaflets | 0.35−0.9 | 100.12 | 4 | |
| Bunch | 0.3−0.5 | 113.95 | 4.33 | |
| Pedicels | 0.63−0.77 | 86 | 3 | |
| Spathe | 0.43−0.51 | 120.5 | 5 | |
| Fibrillium | 0.5−0.8 | 90 | 3.66 | |

**Table 2.6:** The thermal properties of date palm waste according to previous work.

| Date palm parts | Thermal conductivity (W/m.K) | Thermal diffusivity ($m^2.s^{-1}$) | References |
|---|---|---|---|
| Mesh | 0.033 ±0.002 | 1.41 ±0.02 | [69] |
| Mesh | 0.033 ±0.002 | - | [70] |
| Date palm fiber | 0.083 | - | [51] |
| Leaflet | 0.1492 | - | [74] |
| Petioles | 0.081−0.093 | 0.590−0.598 | [75] |
| Bunch | 0.046 ±0.003 | 1.65 ±0.10 | [14] |
| Petiole | 0.042 ±0.003 | 2.16 ±0.15 | |

modulus. While at the base, the waste of the date palm is wood in nature, and it is characterized by insulation and non-conductivity [14, 69, 74, 75], however these properties improve thermal insulation. It is for this reason that several researchers have carried out research on the effect of DP on several types of matrices.

### 2.5.1 DPF reinforced polymeric composites

Petroleum-based plastic (PBP) matrices, encompassing both thermoset and thermoplastic polymers, have undergone comprehensive scrutiny as matrices in the advancement of Diesel Particulate Filter (DPF) composites. Several thermoplastics, such as polyethylene

(PE) [61, 79], polypropylene (PP), thermoplastic starch (TPS), and polyethylene terephthalate (PET) [80], have been employed as the thermoplastic polymeric matrix for DPF composites. In contrast, thermoset polymeric matrices for DPF composites have encompassed materials like polyepoxy, polyester resin [? ], and epoxy resin [61, 74, 81, 82].

Furthermore, it was reported that utilizing DPF with hybrid polymer matrices could enhance the beneficial desired characteristics of the composites such as the tensile strength and modulus, flexural strength and modulus, and thermal properties [81, 83, 84? ]. This demonstrates the effectiveness and competitiveness of DPF as a natural fibre [23] reinforcement to be utilized in developing different composites for a wide range of industrial applications [34]. Table 2.7 summarize the previous research on using both thermoplastic and thermoset polymers as matrix with DPF.

**Table 2.7:** DP reinforced by thermoplastic and thermoset composite.

| Polymer matrix | | Date palm parts | Concentration (%) | Processing technique | Chemical treatment | Optimal fibre (wt%) | References |
|---|---|---|---|---|---|---|---|
| **Thermoplastic** | Polypropylene | Leaf | 27.39.29.19 | Extrusion and injection moulding | Ethanol: Toluene | / | [85] |
| | RPP | Date palm fiber | 30 | Extrusion and injection moulding | Not treated | 30 | [84] |
| | R-PET | Leaf | 5, 10 and 15 | Extrusion and injection moulding | 5% NaOH | 15 | [80] |
| | RLLDPE | Wood powder | (10 to 70) | Melting mixing and compression moulding | Not treated | 70 | [79] |
| | TPS | Spadix stem | 20, 40, 60 and 80 | Compression moulding | 5% NaOH + 5% acetic acid | 50 | [86] |
| | RHDPE + RLDPE + RPP | Leaf | 20 | Extrusion and injection moulding | Not treated | 20 | [79] |
| | LLDPE | Leaflet flour<br>Leaf flour<br>Rachis flour | 45, 60 and 70 | Extrusion and compression moulding | Not treated | 45 | [87] |
| | PVP | Leaf | 10, 20, 26, 30 and 40 | Meltin mixing and injection moulding | Acrylic acid | 26 | [88] |
| | TPS | Spadix stems | 20 | Compression and moulding | 5% NaOH | 50 | [89] |
| | TPS | Mesh | 70, 75 and 80 | Compression and moulding | 5% NaOH | 50 | [90] |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Thermoset** | Polyester resin (8120TEC) | Mesh | 6, 7, 8, 9 and 10 | Compression and moulding | NaOH | 9 | [? ] |
| | Polyester resin (8120TEC) | Mesh | 6, 7, 8, 9 and 10 | Compression and moulding | NaOH | 9 | |
| | Polyester resin | Seed powder | 5, 10, 15, 20 and 25 | Compression and moulding | Not treated | / | [91] |
| | Epoxy resin | Mesh | 35 | Hand lay-up technique | / | 35 | [92] |
| | Polyester resin hardened (methylethyl keton peroxide mekp) | Mesh | 40 | Hand lay-up technique | Alkalin and acid | 40 | [93] |
| | Polyester resin (siropol 7440) | Frond | (10 to 70) | Hand lay-up technique | NaOH and silane | 20 | [94] |
| | Epoxy resin hardened Jointmine 905-3S | Leaf | 50 | Hand lay-up technique | Not treated | 50 | [35] |
| | Epoxy resin | Stem | 5, 10 and 15 | Hand lay-up technique | / | / | [95] |
| | Epoxy resin (LY 556) hardened (HY951) + Eglass fiber | Leaf | 10, 20 and 30 | Hand lay-up technique | Washed with aceton, ethanol and NaOH | 20 | [96] |
| | Epoxy resin | Leaf | 17 | Contact Method | Soxhlet extraction anhydrides | 17 | [97] |
| | Epoxy resin (D.E.R 331) | Stem | 40, 50 and 60 | Mechanical stirring | / | 50 | [76] |

### 2.5.2 DPF Reinforced Inorganic Matrix Composites

DPF has been used in different cementitious composites, such as concrete and mortar as reported by several studies. Other DPF reinforced composites are gypsum and clay bricks composites. The construction industry significantly impacts the environment and contributes to climate change by using large quantities of materials that produce greenhouse gases (GHG), leading to ozone layer depletion [98, 99]. Ordinary Portland cement (OPC) mortars are the most widely used construction materials globally, recognized for their low cost, broad applicability, and availability [100]. However, conventional concrete and OPC cementitious materials have drawbacks such as quasi-brittle characteristics, high compressive strength, low tensile strength, and poor crack resistance [101, 102, 103]. To address these issues and enhance tensile strength and durability properties like thermal shock and fatigue resistance, fiber reinforcement is implemented [100, 104, 105, 106, 107, 108].

Various natural and synthetic fibers are used to restrict crack growth in concrete and OPC materials. Notably, significant efforts have been made to investigate DPF (date palm fiber) as reinforcement for concrete and OPC mortars due to its mechanical properties, abundant availability, low cost, low density, minimal health hazards, processing flexibility (resulting in less machine wear), and the goal of reducing landfill deposits when harvested sustainably [108, 109, 110, 111]. Additionally, DPF has been explored as reinforcement in other construction materials, such as clay, gypsum, and asphalt composites, like OPC/concrete composites. However, most work remains in laboratory studies and has yet to reach commercial production. This section summarizes the current research on the effects of DPF as reinforcement in cementitious, clay, gypsum, and asphalt composite fabrication. Table 2.8 summarize the previous research on using cement, plaster and gypsum as matrix with DPF.

**Table 2.8:** DP/cementitious composites (cement, plaster and gypsum).

| Date palm part | Matrix | Concentration (%) | Dimensions (mm) | Application area | References |
|---|---|---|---|---|---|
| Rachis and petiole | Hemihydrate gypsum | 0, 1.2, 3, 5, 7, 8 and 10 | 3 and 8 | Thermal insulation in buildings | [112, 113] |
| Leaflets | Gypsum | 0, 1, 3 and 5 | 0.5, 1, and 1.5 | Building sectors | [29] |
| Leaf sheath | Gypsum | 0, 2, 4, 6, 8 and 10 | 50 to 300 | Building sectors | [71] |
| Trunk wood | Gypsum | 0, 2, 5, 8 and 10 | 0.7 to 1.1 | Thermal insulation in buildings | [114] |
| Mesh | Cement | 0, 21, 27, 31, 35, 48 and 51 | Diameters (0-0.7) lengths (50-60) | Thermal insulation in buildings | [70] |
| Mesh | Cement | 0, 21, 27, 31, 35, 48 and 51 | Diameter (0-0.7) Length (20-50) | Thermal insulation in buildings | [69] |
| Fiber | Gypsum | 0, 5, 10, 15 and 20 | / | Thermal insulation in buildings | [115] |
| Fiber | Cement | 0, 15, 23 and 62 | / | Construction of buildings | [116] |
| Mesh | Cement | 0, 2, 4, 6, 8 and 10 | 7 to 10 | Construction of buildings | [117] |
| Mesh | Cement | 0, 15, 23 and 62 | Diameter 3 Length 5 | Construction of buildings | [49] |
| Fiber | Lime | 20, 35 and 50 | 0.063 to 5 | Construction of buildings | [48] |
| Fiber | Plaster | 0.5, 1, 1.5 and 2 | 10, 20, 30 and 40 | Construction of buildings | [118] |
| Leaflet | Cement | 0, 6, 12, 18, 24 and 30 | 7 | Thermal insulation in buildings | [119] |
| Rachis and petiole | Cement | 0, 5, 10 and 15 | Diameters (0-3) lengths (0-5) | Construction of buildings | [44] |
| Mesh | Cement | 2 and 3 | 15 and 60 | Construction of buildings | [109] |
| Midribs | Cement | 2 and 3 | 15 and 60 | Construction of buildings | [63] |
| Leaves | Cement | 0.5, 1 and 2 | 0.7-4 | Construction of buildings | [103] |
| Petiole and Rachis | Cement | 5, 10, 15, 20, 25 and 30 | 3 and 6 | Construction of buildings | [120] |
| Mesh | Plaster and cement | 1, 2, 3, 4 and 5 | Diameters (200-300) lengths (300-500) | Thermal insulation in buildings | [111] |
| Date palm fiber | Cement | 0, 1, 2 and 3 | Diameters (0.02 - 0.1) lengths (20 - 30) | / | [121] |

## 2.6 Conclusion

In conclusion, this literature review chapter has provided a comprehensive overview of the existing body of knowledge surrounding the "Energetical Recovery of Bio-waste Applied to Buildings in Algeria." The synthesis of literature has illuminated key themes and challenges in the broader context of waste management, renewable energy, and sustainable construction practices, setting the stage for a focused inquiry into the Algerian landscape.

Furthermore, by examining specific studies related to biowaste recovery and its application in the construction sector, the literature review underscored the need for tailored solutions that account for the unique socio-economic and environmental characteristics of Algeria. The varied methodologies and outcomes presented in the reviewed literature have provided valuable insights, laying the groundwork for the subsequent empirical investigations and analyses in this thesis. As we transition to the empirical chapters, the knowledge synthesized from the literature review serves as a guidepost, informing the design of research methodologies and shaping the investigation into the feasibility and effectiveness of energetical recovery approaches for biowaste in the Algerian built environment. Through the lens of this literature review, we aim to contribute not only to the academic discourse but also to the practical implementation of sustainable and context-specific solutions for biowaste utilization in the construction sector of Algeria.

# Chapter 3

# Materials and Methods

## Summary

## 3.1 Introduction

This chapter is dedicated to detailing the methodologies and materials employed in our investigative journey. The focus of this study is two-fold: firstly, to explore the potential of date palm leaflet, a prevalent biowaste in Algeria, as a sustainable building material; and secondly, to examine its synergistic application with gypsum to form an innovative composite material.

These endeavours are grounded in the broader context of enhancing energy efficiency and sustainability in building materials, which is of paramount importance in the face of global environmental challenges.

## 3.2 Studied Materials

Based on the literature review, the recent statistics, governments policy objectives and analysis of resources regarding the characteristics, availability, and application areas of date palm waste, and in line with our goal to enhance construction materials through the utilization of these by-products.

After thoroughly analysing the data presented in these articles, it becomes evident that the midribs and leaflets constitute the most discarded components of the date palm. Table 1 summarizes the percentages of palm waste during a year in different countries. These parts are often deemed the least useful in terms of practical applications. In this current study, we have specifically focused our attention on the leaflets of the date palm.

### 3.2.1 Date palm leaflet (DPL)

The date palm component investigated in this study was obtained from leaf debris, particularly leaflets 3.1, served as the raw material for this work of art. Harvested in the geographic regions of Tolga and Biskra in Algeria, these trees have special characteristics that allow them to grow under various conditions, such as deserts and hot environments [34].

The leaves of the date palm are long and pinnate with a good arrangement and its leaflets are sharp. Every year, 10 to 20 new leaflets grow. The rachis of date palm leaves is surrounded by a strong fibrous sheath [33]. With the aim of utilizing date palm by-products, this research efforts focused on the Deglat Noor and Mch Deglat variety, which has the greatest diversity in this area.

**Figure 3.1:** Date palm leaves.

### 3.2.2 Composite Material (Gypsum/DPL)

#### 3.2.2.1 Gypsum

Gypsum plaster, extensively used in building construction as a wall coating and for roofing ceilings, enjoys global popularity due to its unique properties like malleability and low density. This material is produced by extracting and heating gypsum at a high temperature of 150, as outlined in equation 3.1 [122]. When mixed with water, gypsum plaster forms a soft paste after setting, offering greater workability compared to cement mortar. Despite its advantages, the low thermal properties of gypsum plaster have been a focal point in research. Numerous studies aim to enhance its thermophysical properties by integrating natural and ecological additives. Among various reinforcements, glass and sisal fibers have emerged as the most prevalent [123]. The gypsum plaster used in this investigation aligns with these research trends, chosen for its compatibility with such additives to potentially improve its application in construction [6, 114, 115].

$$2CaO_4.4H_2O + Heat \implies 2CaSO_4.H_2O + 3H_2O \tag{3.1}$$

The ratio of water to gypsum (w/g) has the potential to range from 0.4 to 0.8 during the mixing procedure, or conceivably even surpass these values. As water is combined with the powdered form of gypsum, it undergoes a conversion and is transformed into gypsum. The gypsum used in this study was obtained from the GNMC company in Biskra city in Algeria (3.2). It is combined with water at a mass ratio of 0.6. The findings of the research suggest that the density of this specific gypsum is 995.89 $Kg/m^3$, which is the same as a thermal conductivity of 0.8 $W/m^2K$.

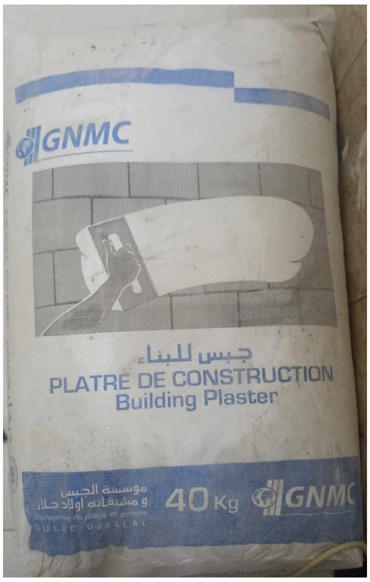


**Figure 3.2:** Gypsum of GNMC company in Biskra.

## 3.3 Study Processes

The research methodology adopted in this study, as detailed in Chapter One, and illustrated in figure 3.3, centres on the comprehensive characterization of the material under scrutiny, specifically date palm waste. This initial step is crucial before integrating the waste as reinforcement into either a known or a new matrix. The characterization process of the date palm is segmented into three distinct phases: morphological, physicochemical, and thermal analysis. The decision to use gypsum as a binding material was influenced by its compatibility with the inherent properties of the date palm.

The selection of a water-to-powder ratio (W/P) of 0.6 was informed by recommendations from previous studies, with the intention of employing this composite material in construction and insulation applications. Granulometric analysis involved determining the most common particle sizes in the date palm leaflet post-grinding process of the leaflets.

Furthermore, the investigation into the gypsum/date palm leaflets composite was executed through thorough experimental tests and analyses, emphasizing the variation in concentrations and particle sizes of the date palm leaflet powder to evaluate its effects on the composite material's properties.

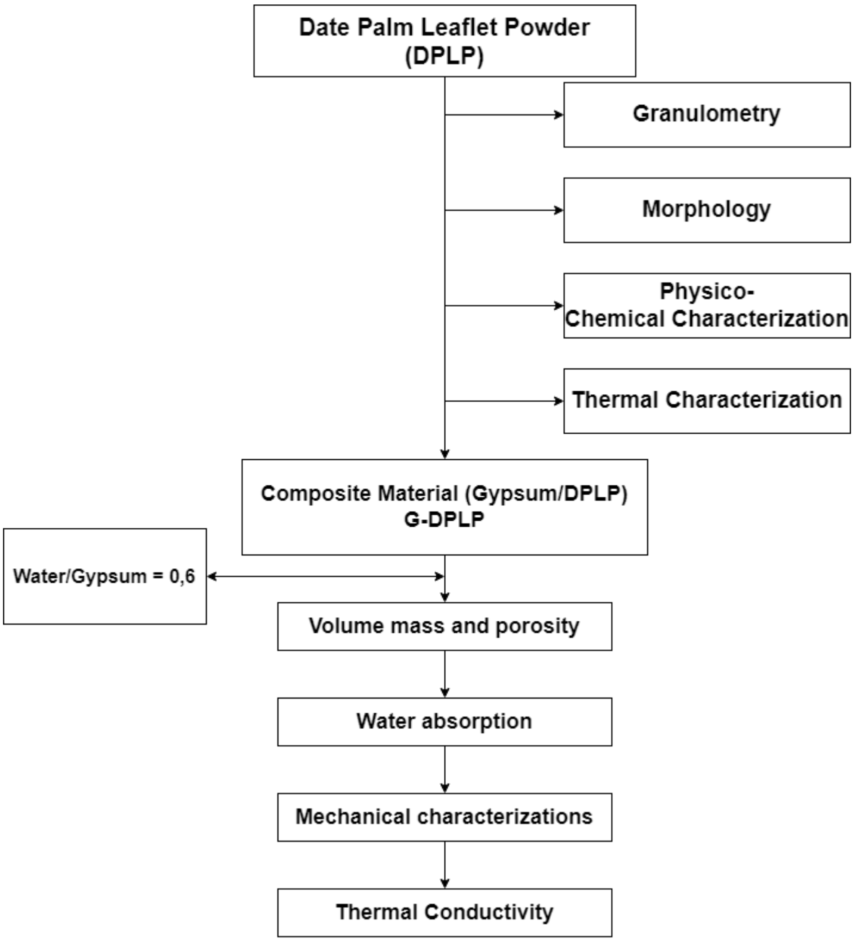


**Figure 3.3:** Studying process.

## 3.4 Characterizatino of the DPL

### 3.4.1 Preparation of the raw material

Date palm leaves were selected and collected from various oases and date palm varieties in the city of Biskra, Algeria. Two categories of date palms were selected (Deglat Noor and Mch Deglat) from three different sites to study their leaf remains. Bouchagroune Oasis, Mekhadma, and Lichana are known worldwide for their exceptional dates production.

Sixth sample set consists of Deglet Noor Bouchagroune (DN -B), Deglet Noor Mekhadma (DN -M), Deglet Noor Lichana (DN -L), Mch Deglet Bouchagroune (MD -B), Mch Deglet Mekhadma (MD -M) and Mch Deglet Lichana (MD -L). The types, regions, and data for the date palm leaflets samples used in this study are tabulated in Table 3.1.

The leaflet was separate from the midribs, we washed the leaflets and dried them at a temperature of 40 °C to eliminate the water contained. The leaflets were crashed with a grinder after being properly dried, as you see in the figure 3.4. After being ground, the powder was finally sent through an automatic sieve to separate the different sizes. Our raw material were prepared by the method followed by Kethiri et al. [58].

**Figure 3.4:** Date palm Leaflet powder after grinding and sieving

**Table 3.1:** Samples names and their category.

| Type of wood | Region | Category | Abbreviation |
|---|---|---|---|
| Date palm leaflet | Bouchagroune | Deglat Noor | DPL-DN-B |
| | | Mch Deglat | DPL-MD-B |
| | Mekhadma | Deglat Noor | DPL-DN-M |
| | | Mch Deglat | DPL-MD-M |
| | Lichana | Deglat Noor | DPL-DN-L |
| | | Mch Deglat | DPL-MD-L |

### 3.4.2 Density of DPL

The study focuses on measuring the density of date palm fibre powder, a crucial aspect for its industrial application. This measurement will follow ASTM C642-13 [124], a standard for determining the density and specific gravity of plastics by displacement, applicable for solid materials including powders.

The aim is to accurately determine the bulk and true density of the powder, essential for understanding its properties for use in composite materials, thermal insulation, and filtration systems. Adhering to this standard will provide detailed insights into the physical properties of date palm fibre, enhancing its potential in various applications.

### 3.4.3 Mercury Intrusion Porosimetry (MIP)

The research uses Mercury Intrusion Porosimetry (MIP) to assess the pore structure of date palm leaflet, focusing on pore size distribution, volume, and surface area. The study adheres to ASTM D4404-18 [125], ensuring accurate porosity measurements.

The aim is to understand the porosity characteristics of the powder, important for applications in filtration, adsorption, and material science. By following this ASTM standard, the research aims to provide detailed insights into the microstructural porosity of the powder for various industrial and research uses.

**Figure 3.5:** Porosimetry.

### 3.4.4 Scanning Electron Microscopy/Energy Dispersive X-Ray Analysis (SEM/EDX)

These two techniques are often used together in a single instrument, 3.6. SEM provides detailed images of the surface morphology, while EDX adds the capability of elemental analysis. This combination is particularly powerful for investigating the microstructure of materials, understanding defects, and analysing foreign materials in failure analysis, quality control, and research settings. In practical terms, the SEM provides a high-resolution image, and the EDX gives the elemental composition of the specific points, lines, or areas in that image. This combination allows for a comprehensive understanding of both the structure and composition of the sample at a microscopic level.

In this study, Scanning Electron Microscopy (SEM) and Energy-Dispersive X-ray Spectroscopy (EDX) are used to analyse the microstructural and elemental composition of date palm leaflet. SEM will visualize the surface morphology, while EDX will quantify and map the elements, adhering to the same standard. This combined approach aims to provide a detailed understanding of the material's microstructure and elemental distribution, essential for material science applications. Adherence to ASTM standards [126] ensures the study's quality and reproducibility, making it a reliable method for characterizing similar bio-based materials.


**Figure 3.6:** Scanning electron microscope

### 3.4.5 X-Ray diffraction analysis (XRD)

This research focuses on characterizing the crystalline structure and phase composition of date palm leaflet through X-Ray Diffraction (XRD) analysis, strictly following ASTM standards. The goals are to identify and quantify the crystalline phases, analyse lattice parameters, and detect structural irregularities, adhering to ASTM E1777-96 2018 [127] for particle size accuracy. This methodical approach ensures reliable and precise XRD results, which are anticipated to offer significant insights into the microstructural properties of the date palm leaflet. These findings could impact its use in biomaterials, pharmaceuticals, and food technology, setting a standard for analysing crystalline materials in similar studies.


**Figure 3.7:** X-Ray diffractometer

### 3.4.6 Fourier Transform Infrared Spectroscopy (FTIR)

This study uses Fourier Transform Infrared Spectroscopy (FTIR) to analyse the molecular composition and functional groups in date palm leaflet, following ASTM E1252-98 2018 standards [128]. The objective is to identify specific bonding structures and organic compounds, enhancing understanding of the material's chemical interactions and properties. This methodology ensures accurate, reproducible results, offering insights into the chemical makeup of the powder for applications in food science, pharmacology, and materials engineering. Adhering to these ASTM protocols ensures rigorous analysis, crucial for understanding the material's molecular structure and its practical applications.

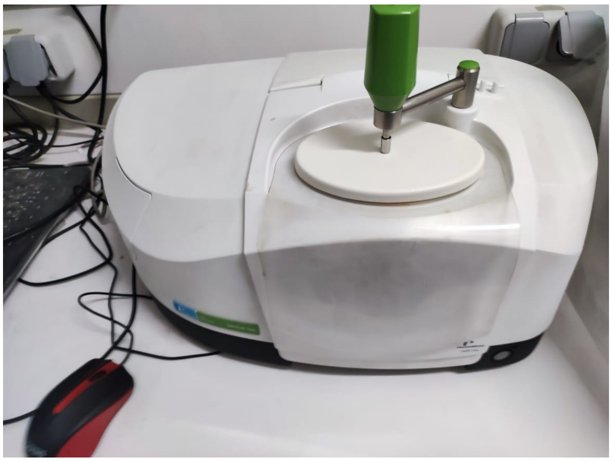

**Figure 3.8:** Fourier Transform Infrared Spectroscopy instrument

### 3.4.7 Thermogravimetric analysis (TGA)

This study employs Thermogravimetric Analysis (TGA) to examine the thermal stability and composition of date palm leaflet, focusing on weight loss, decomposition temperatures, and residual mass. The analysis adheres to ASTM E1131-20 2020 [129] for temperature calibration and data interpretation, and for compositional analysis. This approach aims to understand the material's thermal degradation and stability, with potential applications in biodegradable materials, thermal insulators, and food packaging. Following these standards ensures precise and dependable TGA results, making the study a valuable reference for thermal analysis in this field.

**Figure 3.9:** Thermogravimetr instrument

## 3.5 Characterization of the Composite Material (Gypsum/DPL)

### 3.5.1 Granulometry

The studied DPL recovered from three different regions in Biskra is dried with natural solar drying and, after, is ground to have small aggregates. A series of tests are conducted to determine the particle size distribution. The results discussed below are an average of fourth measurements. The particle size distribution is determined by the sieving method according to the French standard 18-560 (NF P18-560 1990) [130].

The result of the distribution size analysis, granulometry, is shown in figure 3.10. The particle size distribution ranges from 0.125 mm and 1.5 mm. Figure 3.10 shows that the proportion of DPL particles between 0.125 and 0.25 mm is less than 40%. On the other hand, the proportion of particles between 0.5 and 1.5 mm is more than 85%. The diameters of 0.5, 1, and 1.5 mm represent the dominant part of the date palm leaflet. This result is an important feature of the DPL to see the percentage of each particle size to better choose the range in which we study. Also, to see the effect of particle size variation on the behaviour of the material.

### 3.5.2 Preparation of the composite material

During our preparation of the samples, we took into consideration the American standards (ASTM C28/C28M-10 2015) [131] and several parameters that can influence on our results. We set the water/gypsum ratio to 0.6 that was used by [112, 113, 115, 118]. Also Al-Rifaie and Al-Niami [71] said that the w/g = 0.6 gives the best results in terms of composite properties. But on the other hand, we have varied in the dimensions of the

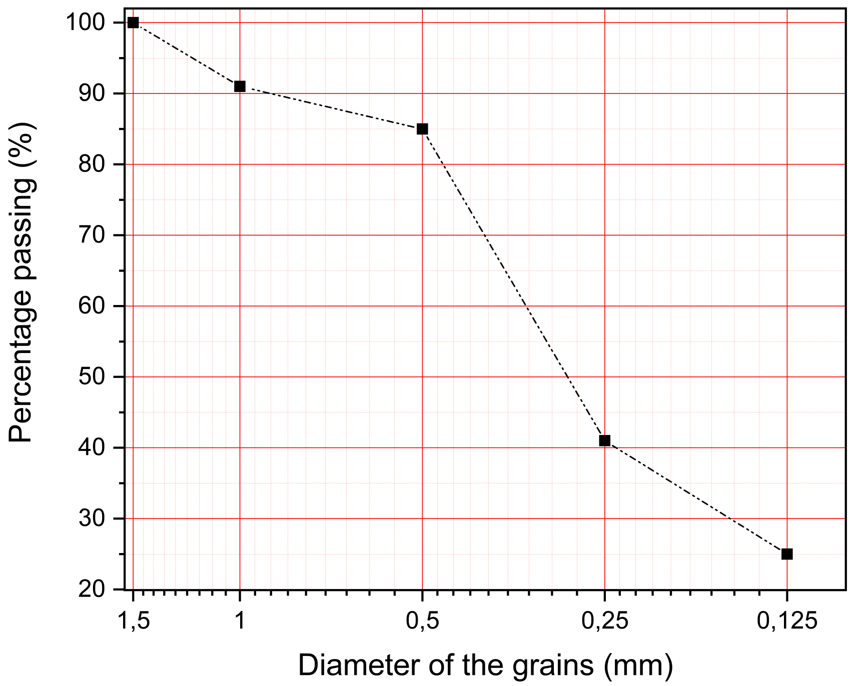


**Figure 3.10:** DPL size distribution.

diameters of the powder and on the mass fraction of the powder in the mixture [26, 27]. For the dimensions we have chosen 0.5, 1 and 1.5 mm according to the particle size test in figure 2.2 above. Because this interval represents 90% of the crushing fibre. And for the gypsum/DPL ratio we used the following fractions 0, 1, 3, and 5% for each dimension.

Mixing of the slurry followed by electrical mixer of mortar TC-MX 1400-2 E (1400 W, Electronic dimmer, Lockable switch, Soft start, Solid tool holder; with mortar mixing paddles plaster, concrete, cement, paint 100 mm x 600 mm. Precautions were taken to ensure homogeneity and complete compaction by a vibrating Tab. Date palm fibers were added to the plaster slurry after the gypsum had first been premixed with water to remove the fibers in the specified quantities. All mixing was done with tap water and at a temperature of 24 °C. The setting time was not altered by the application of a retarder or adjuvant.

### 3.5.3 Density & porosity

In our research, we focus on determining the density and porosity of a gypsum/date palm fibre composite building material. The objective is to calculate the material's density using the standard ASTM C642-13 [124], which provides a method for the accurate measurement of density and specific gravity of solid materials. This will allow us to assess the composite's overall mass-to-volume ratio, a crucial factor in its structural and physical properties.

**Table 3.2:** Specimens names and their category.

| Concentration (wt. %) | Dimension (mm) | Names |
|---|---|---|
| 0 | - | Reference |
| 1 | 0,5 | G-DPL-1-0.5 |
| | 1 | G-DPL-1-1 |
| | 1,5 | G-DPL-1-1.5 |
| 3 | 0,5 | G-DPL-3-0.5 |
| | 1 | G-DPL-3-1 |
| | 1,5 | G-DPL-3-1.5 |
| 5 | 0,5 | G-DPL-5-0.5 |
| | 1 | G-DPL-5-1 |
| | 1,5 | G-DPL-5-1.5 |

For porosity, we aim to employ mathematical calculations based on the volume and mass data obtained, in line with principles outlined in relevant ASTM standards. This method will enable us to estimate the void fraction within the composite, which is vital for understanding its insulation properties and overall performance in building construction. By adopting these standards and mathematical approaches, we intend to provide a comprehensive analysis of the physical characteristics of the gypsum/date palm fibre composite, essential for its application in sustainable and efficient building designs.

### 3.5.4 Water absorption

Water absorption tests play a vital role in evaluating the durability, suitability, and performance of composite materials, including our gypsum/DPL material. This test involves immersing a specimen of the material in water for a specific duration and then measuring the quantity of water absorbed. Regulatory and industry bodies, such as the American Society for Testing and Materials (ASTM), often specify the standard procedures for this test. For instance, ASTM has formulated several standards, including ASTM C642-13 [124], which outlines the general process for water absorption tests of composite materials.

Before conducting the water absorption experiments, the composite specimens underwent desiccation at a temperature of 65 °C for seven days, until they attained a state of equilibrium in weight. Subsequently, the composite materials were subjected to an assessment of their water absorption capacity on days 7, 14, and 28.

### 3.5.5 Mechanical test

In our study, we aim to assess the mechanical performance of a composite material made from gypsum and date palm fibre, with a particular focus on its compression and flexural strength. These properties are crucial indicators of the material's structural integrity and suitability for use in construction. To evaluate the compression strength, we will adhere to ASTM C109/C109M-20 [132], which outlines the procedures for evaluating the compressive strength of hydraulic cement mortars using 2-inch cube specimens. This standard is essential for understanding how the composite material behaves under compressive loads.

For the flexural strength assessment, we will follow ASTM D790 [132], the standard test method for flexural strength of hydraulic-cement mortars. This will provide insights into the material's ability to withstand bending stresses. The results from these tests will be crucial in determining the practical applications of the gypsum/date palm fiber composite in building construction, offering a sustainable alternative to traditional building materials. By utilizing these ASTM standards, our study aims to provide a comprehensive evaluation of the composite's mechanical properties, contributing to the development of more sustainable construction materials.

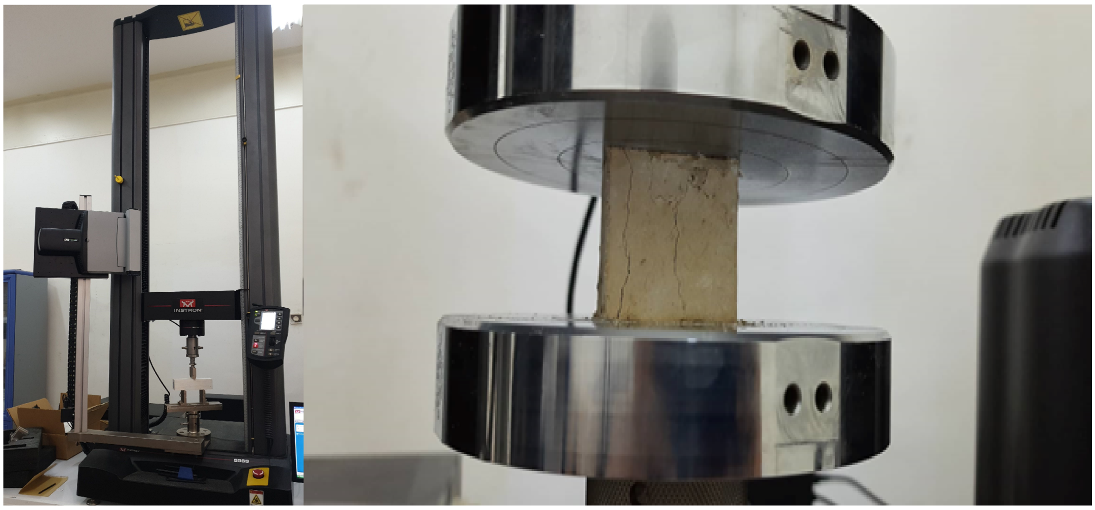

**Figure 3.11:** Instron machine for Mechanical test.

### 3.5.6 Thermal conductivity

In this research, we focus on evaluating the thermal properties of a gypsum/date palm fibre composite, specifically its thermal conductivity and calorific power. Understanding these properties is essential for determining the material's efficacy as an insulator and its energy efficiency in building applications. To measure thermal conductivity, we will utilize ASTM C518-21 [133], a standard that provides a method for determining steady-state thermal transmission properties. This test will allow us to assess how effectively the composite conducts heat, a crucial factor in its insulation performance.

This standard outlines the procedure for determining the gross calorific value of refuse-derived fuel by the bomb calorimeter method. By applying these ASTM standards, we aim to comprehensively characterize the thermal behaviour of the gypsum/date palm fibre composite. The results will provide valuable insights into the material's potential as a sustainable and energy-efficient building material, contributing to the development of environmentally friendly construction practices.

## 3.6 Conslusion

The concluding section underscores the development of a comprehensive framework for assessing date palm leaflet as a sustainable construction material. This framework, conforming to rigorous testing standards, guarantees thorough and pertinent evaluation of the raw material and its composite form when combined with gypsum.

The study highlights the significant advantages of utilizing local biowaste in Algeria's construction industry, with objectives centred on enhancing sustainability, minimizing environmental impact, and complying with regional industry norms. The insights derived from these methodologies provide a fundamental basis for subsequent chapters, emphasizing the study's role in advancing sustainable development and ecological sustainability within the Algerian construction sector.

# Chapter 4

# Results and Discussions

## Summary

## 4.1 Introduction

This chapter presents and analyses research results on using biowaste, particularly date palm fiber combined with gypsum, as a sustainable building material. It focuses on validating this material's potential within the Algerian context, systematically discussing findings in relation to the thesis's objectives and hypotheses.

The results are critically evaluated to conclude on the material's properties and parameters, assessing how they meet the goals of enhancing sustainability and energy efficiency in Algerian building materials. The chapter not only details these empirical findings but also interprets them, linking the data to both practical applications and broader implications in sustainable construction and biowaste utilization.

## 4.2 DPL Results

### 4.2.1 SEM

The microstructure of DPL was illustrated in Figure 1, which contains six SEM images of DPL sample. The SEM images presented in Figure 1 shows six different variants of date palm leaf powder, designated $(1-DN-B)$, $(2-MD-B)$, $(3-DN-M)$, $(4-MD-M)$, $(5-DN-L)$, and $(6-MD-L)$, each consisting of a unique combination of nanofibers and nanoparticles of different sizes.

The surface of date palm fibers has a cylindrical shape, same results were found by [119]. In addition, the surface appears rough and consists of numerous filaments, cells, and pores, as reported by [115]. The rough surface consists mainly of impurities and residual lignin, which is a typical feature of most samples according to [14, 134].

The images show that each sample contains a mixture of nanofibers and nanoparticles, each with its own size. Remarkably, the Deglat samples were found to have a higher percentage of particles classified as $(1-DN-B)$, $(3-DN-M)$, and $(5-DN-L)$ compared to fibres when compared to other samples. The SEM images also shows that the particles have a diameter of $10-50$ $\mu m$, while the fibres have a diameter of $100-500$ $\mu m$ for DPL samples. Table 4.1 summarizes some results of this analysis. Finally, it can be deduced that the samples consist of a mixture of fibres and particles that have a wide range of diameters and lengths, ranging from $10-50$ $\mu m$ and $100-500$ $\mu m$, respectively [135].

**Table 4.1:** Dimension of the particles.

| | DN-B | MD-B | DN-M | MD-M | DN-L | MD-L |
|---|---|---|---|---|---|---|
| Diameter ($\mu m$) | 40 - 50 | 20 - 30 | 40 - 50 | 10 - 20 | 10 - 20 | 20 - 30 |
| Length ($\mu m$) | 100 - 150 | 350 - 400 | 250 - 300 | 450 - 500 | 200 - 250 | 250 - 300 |

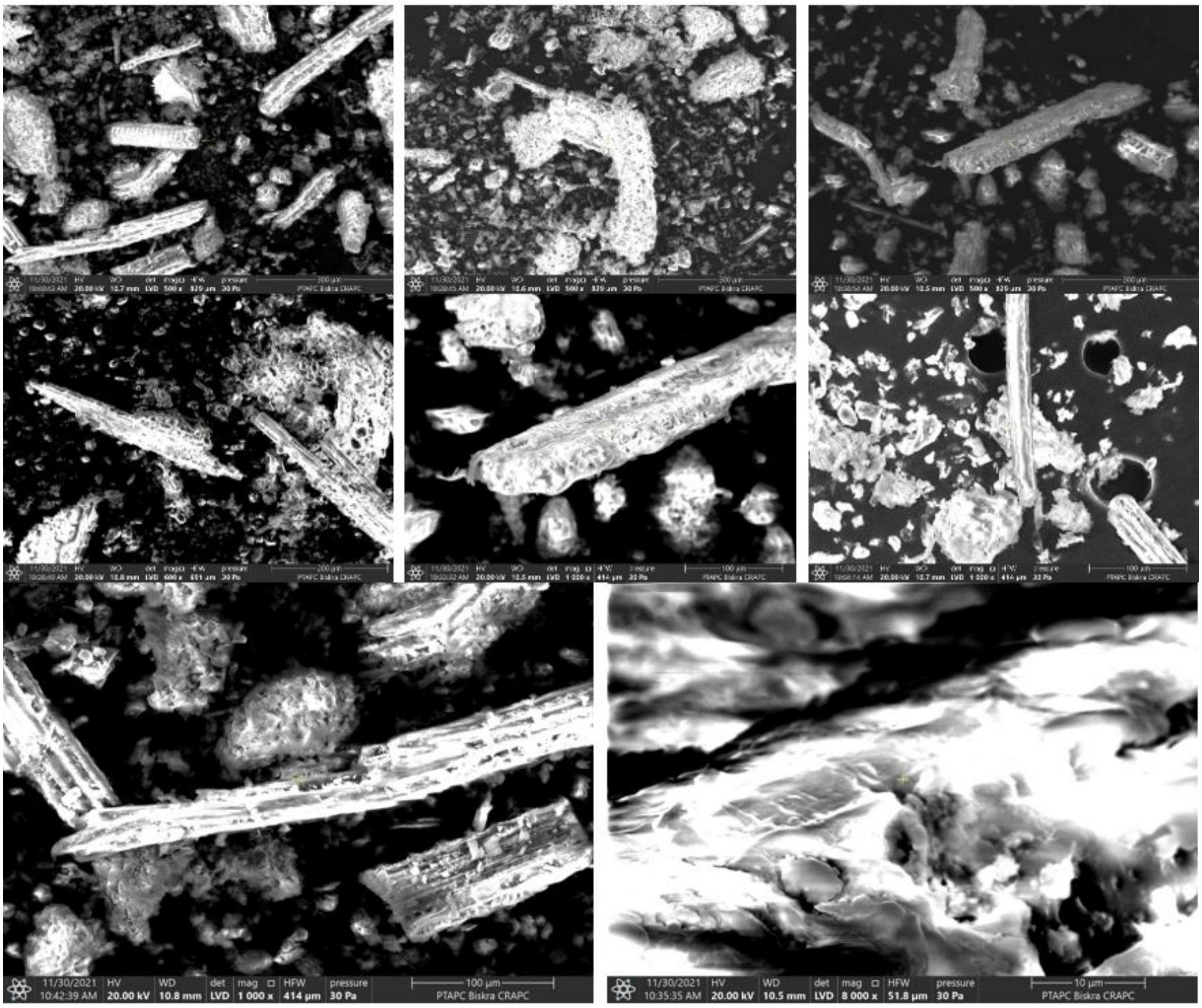

**Figure 4.1:** SEM images of DPL powder

### 4.2.2 Density

Density is an important physical parameter in materials science that we can use to get an idea of whether this material is heavy and bulky or the opposite. Table 4.3 shows the physical properties of the six DPL varieties. The apparent density of the DPL samples is 494.782 $\pm$ 9 ($Kg/m^3$). The absolute density of the samples is 872,457 $\pm$ 21 ($Kg/m^3$). The porosity of the DPL samples is 43 $\pm$ 9 %.

According to the literature [5, 13], leaflets are classified as very light wood, which makes them soft and easy to handle. The date palm fibre has a lower density compared to other natural fibres, so this property can lead to having the low-density composites. On the hand, it is an advantage for reducing industrial consumption [34]. On the other hand, it influences other properties and consequently influences its processing and utilization.

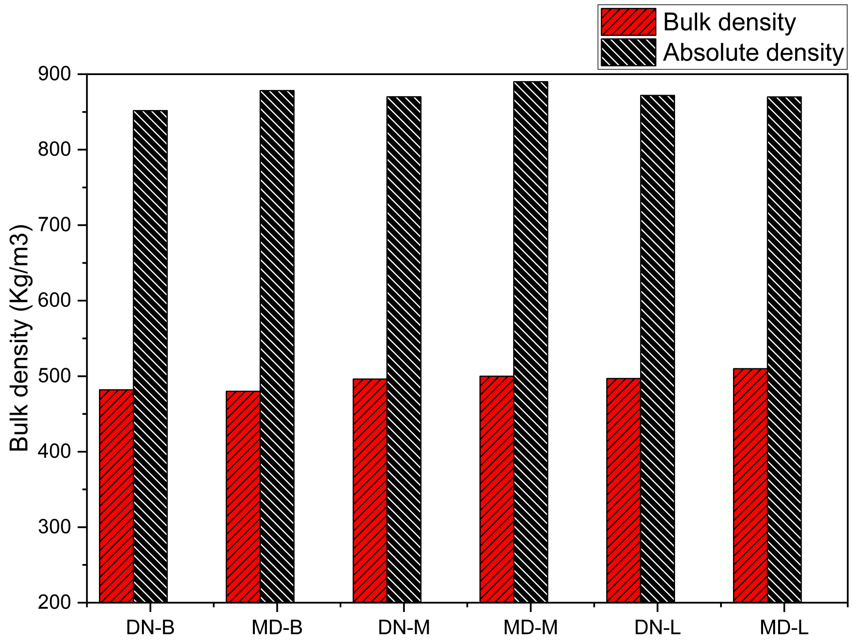


**Figure 4.2:** Density of DPL samples.

### 4.2.3 MIP results

The MIP test provides a lot of important information such as, density, porosity, pore size and distribution about the specimens studied. In Figure xx, the bulk density at 0.23 psia is shown, with the bulk density represented by columns and porosity by a line for each specimen. The maximum value bulk and apparent density were represented by the first sample, which consisted of gypsum and lime. It was observed that each time DP was added, a decrease in bulk and apparent density occurred. Additionally, when fibers of long dimensions were added, a significant decrease in bulk and apparent density was also noted. It was noted that the DP occupies a volume within the matrix, and due to its low density, this explains the overall decrease in the bulk and apparent density.

The porosity is also shown in Figure xx, represented by a line. It is directly related to the ratio between the apparent density and the true density. The minimum value of porosity was observed in the specimens consisting of gypsum and lime. It was observed that porosity increased with each addition, whether in weight percentage (wt.%) or in the dimensions of DP. The increase in porosity was also caused by the occupation of volume by DP within the matrix. All results obtained from the MIP methods were summarized in the table 4.2.

**Table 4.2:** The MIP results for DPL samples (Bulk Density, Apparent Density, Median pore, and Porosity).

| Samples | Bulk density at 0.23 psia ($g/mL$) | Apparent density ($g/mL$) | Porosity (%) |
|---|---|---|---|
| DPL (0,5 mm) | 0.258 | 0.5152 | 49.927 |
| DPL (1 mm) | 0.3529 | 1.3510 | 58.0701 |
| DPL (1,5 mm) | 0.5665 | 1.5743 | 77.5862 |

### 4.2.4 EDX

The EDS analysis showed us the chemical composition of our studied powder. Our powder contains several components with different concentrations. Figure 4.3 shows the concentrations of the three main components according to their nature. Carbon, oxygen and silicon dominate, a result also reported by [10, 14, 58], in the concentration ranges (45.2 – 64.78%), (33.61 – 47.45%) and (1.79 – 4.02%). It also excites other compounds such as Na, Mg, Al, S, Cl, K, Ca, and Fe with low concentrations.

The presence of carbon in these enormous amounts is proved by the EDS and by its enhancement in the SEM images. Table 4.4 summarizes some results of this analysis and compares them with other concentrations of the same components in the same and other parts of the date palm.

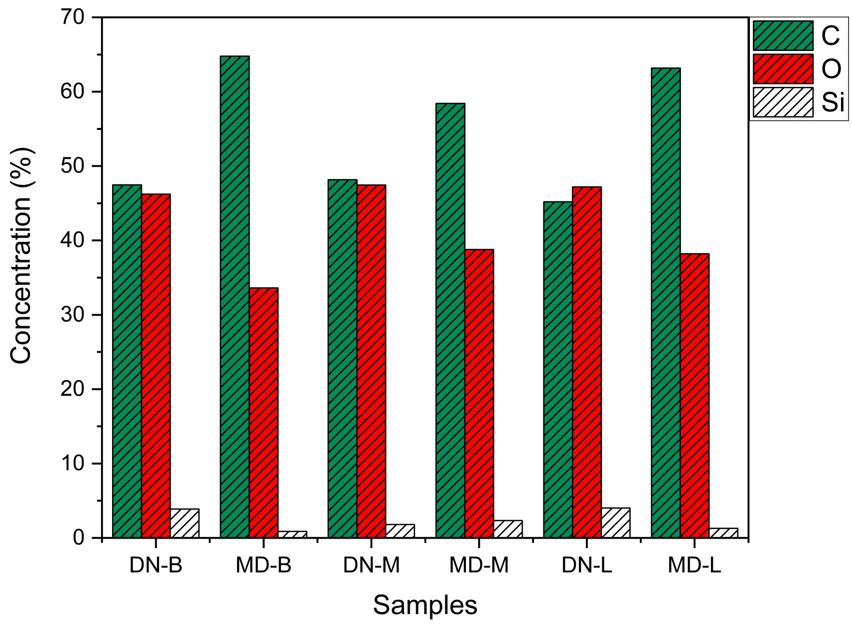


**Figure 4.3:** Concentration of DPL chemical composition.

**Table 4.3:** Density and porosity of the DPL.

| | Present work | | | | | | References | | |
|---|---|---|---|---|---|---|---|---|---|
| | DN-B | MD-B | DN-M | MD-M | DN-L | MD-L | [13] | [136] | [117] |
| Bulk density ($Kg/m^3$) | 481.897 | 479.898 | 496.093 | 500.001 | 496.908 | 509.897 | 411 | 560 | 512 |
| Absolute density ($Kg/m^3$) | 851.645 | 878.232 | 870.098 | 889.987 | 871.876 | 869.908 | 830 | / | 1300 |
| Porosity (%) | 42 | 45 | 44 | 44 | 43 | 41 | 50.6 | / | 40.1 |

**Table 4.4:** Chemical composition of DPL.

| | Present work | | | | Literature studies | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C (A%) | O (A%) | Si (A%) | Mg (A%) | C (A%) | O (A%) | Si (A%) | Mg (A%) | Type | Variety | Region | References |
| DN-B | 47.47 | 46.23 | 3.88 | 0.53 | 43.95 | 47.08 | 0.69 | 1.52 | Leaflet | Deglat Noor | Mekhadma, Algeria | [14] |
| MD-B | 48.17 | 47.45 | 1.80 | 0.56 | 57.89 | 40.09 | 0.48 | 0.03 | Leaflet | Gherss | El-Oued, Algeria | [10] |
| DN-M | 64.78 | 39.38 | 1.79 | 0.13 | 42.67 | 48.19 | 0.28 | 0.04 | Bunch | Deglat Noor | Mekhadma, Algeria | [14] |
| MD-M | 60.02 | 41.89 | 3.54 | 1.02 | 59.27 | 40.73 | / | / | Spath sheaths | / | El-Oued, Algeria | [137] |
| DN-L | 58.41 | 38.79 | 2.34 | 0.05 | 45.41 | 49.43 | 1.08 | 0.43 | Leaflet | Deglat Noor | Bouchagroune, Algeria | [58] |
| DN-M | 45.2 | 33.61 | 4.02 | 0.42 | / | / | / | / | / | / | / | / |

### 4.2.5 XRD

In the study, six samples (DN − B, DN − M, DN − L, MD − B, MD − M, and MD − L) of DPL were analysed using the X-ray diffraction (XRD) test. The XRD patterns of all the samples showed two main peaks, one at $2\theta = 21.4$, 21.41, 21.85, 21.58, 21.45 and 21.4 °, and a weaker one at $2\theta = 16.99$, 17.99, 17.99, 18, 17.89 and 18.19 °, as you observe in figure 4.4. The highest peaks correspond to (111) and (002) silicon oxide-ethylene glycol (12/2) (JCPDS No. 98-006-6118) that are affected by the presence of many impurities existing in the biomass of the date palm. Previous studies by [11, 45] had suggested that these peaks were corresponding crystallographic planes (110) and (200) typical of native cellulose. Further analysis showed that all the samples were of cellulose type I, based on the presence of these peaks in their XRD patterns. The samples had a high order level in the cellulose crystals at the fibre level, as indicated by the crystallinity indices, which ranged from 46,496% to 52,941%. These findings were consistent with those made by [60].

The Scherrer equation was used to calculate the Cr (%) and the Cr (%) of the samples, with the results ranging from 49.900 to 62.841. Table 4.5 summarizes some results of this analysis and compares them with the previous work. These findings suggest that the DPL samples have a significant amount of crystalline cellulose compared to amorphous material.

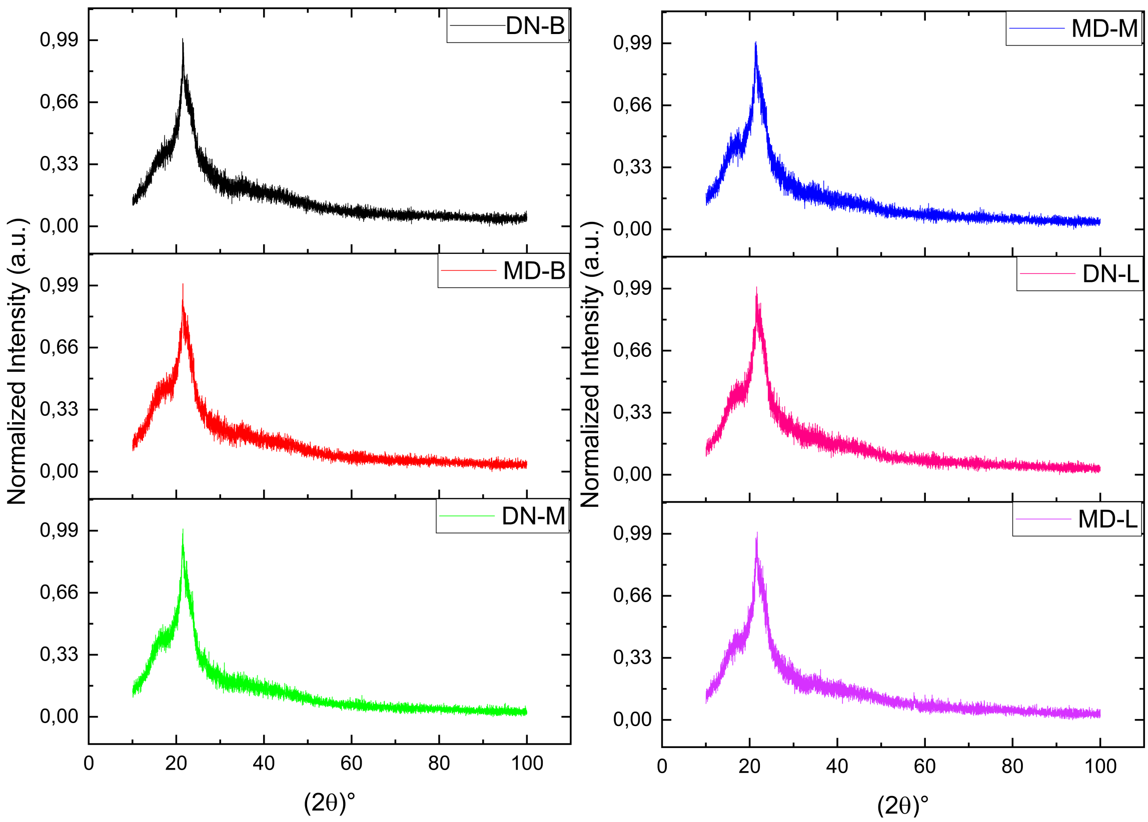


**Figure 4.4:** XRD patterns of DPL (DN-B, MD-B, DN-M, MD-M, DN-L, and MD-L)

**Table 4.5:** XRD Peak position of DPL.

| | Present work | | | | | | References | | |
|---|---|---|---|---|---|---|---|---|---|
| | DN-B | MD-B | DN-M | MD-M | DN-L | MD-L | [11] | [10] | [58] |
| Peak position | 16.89 | 17.99 | 18.29 | 18 | 17.89 | 18.59 | 16.19 | 15.86 | 17.99 |
| | 21.4 | 21.41 | 21.85 | 21.58 | 21.45 | 21.4 | 22.14 | 22.2 | 21.4 |
| CI (%) | 62.841 | 54.3603 | 62.125 | 62.637 | 60 | 49.900 | 69.95 | 65.71 | 42.9005 |
| Cr (%) | 46.792 | 49.319 | 50.788 | 52.941 | 46.496 | 49.641 | 57.04 | 45.53 | 48.6413 |

### 4.2.6 FTIR

The DPL was analysed by infrared spectroscopy (FTIR). The transmittanc spectrum of the DPL is shown in Figure 4. In general, the results of these studies show different peaks in the range between 1000 $cm^{-1}$ and 4000 $cm^{-1}$ [39]. From figure 4, it is clear that the peak at 3330 $cm^{-1}$ is associated with the O−H stretching vibration found in cellulose, hemicelluloses and lignin [11].

The two sharp peaks at 2940 $cm^{-1}$ and 2800 $cm^{-1}$ , a result also reported by [80, 138, 139] are attributed to the asymmetric and symmetric C-H stretching vibrations of CH and CH2 in cellulose and hemicelluloses, respectively [45].

The C=O stretching at peak 1750 $cm^{-1}$ is associated with cellulose, hemicellulose and lignin [80, 138, 139]. The two peaks at 1646 $cm^{-1}$ and 1597 $cm^{-1}$ are attributed to the O−H bending vibrations of the water absorbed by the cellulose and the C=O stretching of the carboxylic acid and ester, respectively [45]. A very strong peak at 1027 $cm^{-1}$ was assigned to the C−O stretching of cellulose [138, 140]. The main constituents of this fibre are carbon, hydrogen, and oxygen, which ensure that the fibre is organic in nature. The FTIR result confirms the images of SEM and EDS and shows that the DPL contains C, H and O in high concentration. These elements are combined in different functional groups characterized by different stretched wave numbers, such as hydroxyl (O−H), hydrocarbon (C−H) and carbonyl (C−O).

### 4.2.7 TGA

The thermal properties of date palm samples were investigated to assess their suitability for various applications. Figure 4.6 illustrates the TGA curves of $DN-B$, $DN-M$, $DN-L$, $MD-B$, $MD-M$, and $MD-L$, respectively. The first stage ($35-115$ ° C) indicated all samples lost weight due to the evaporation of moisture [141].

Subsequently, in the second degradation stage, which approximately started at 200 ° C for all fibre types, a significant reduction constituent, including holocellulose and lignin, etc [141, 142]. These findings align with previous research conducted by [143, 144], who

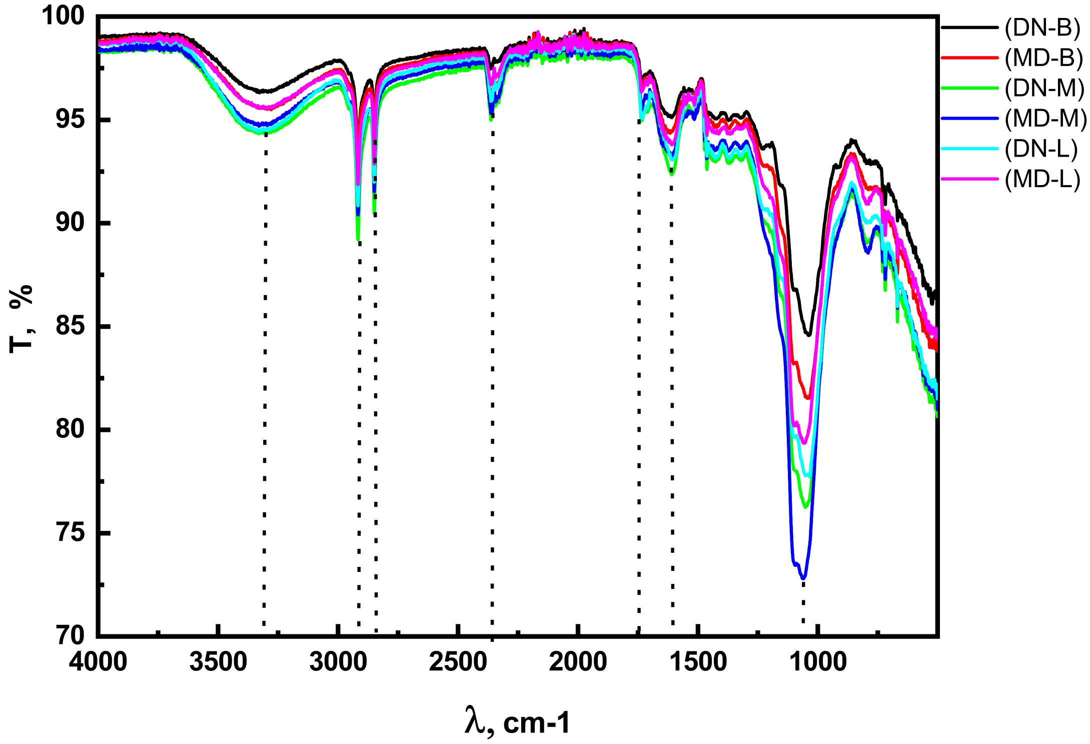


**Figure 4.5:** FTIR spectroscopy of DPL (DN-B, MD-B, DN-M, MD-M, DN-L, and MD-L).

utilized fibers from fruit bunch branches of Algerian date palm trees, and by [141], who employed two different natural fibers, namely Washingtonian trunk fibers and pineapple fibers. The thermal stability of all date palm fibers was found to be consistent and comparable to other fibres as shown in table 4.6, that validates their potential as suitable reinforcing materials for high-temperature applications.

**Table 4.6:** Thermal gravimetric data of DPL.

| Samples | TGA | | | |
|---|---|---|---|---|
| | T onset $(°C)^a$ | T peak $(°C)^b$ | W loss $(\%)^c$ | W residue $(\%)^d$ |
| DN − B | 243 | 304 | 70.70 | 29.30 |
| MD − B | 255 | 304 | 69.80 | 30.20 |
| DN − M | 259 | 303 | 70.62 | 29.38 |
| MD − M | 251 | 300 | 70.76 | 29.24 |
| DN − L | 253 | 300 | 70.03 | 29.97 |
| MD − L | 259 | 308 | 70.20 | 29.80 |

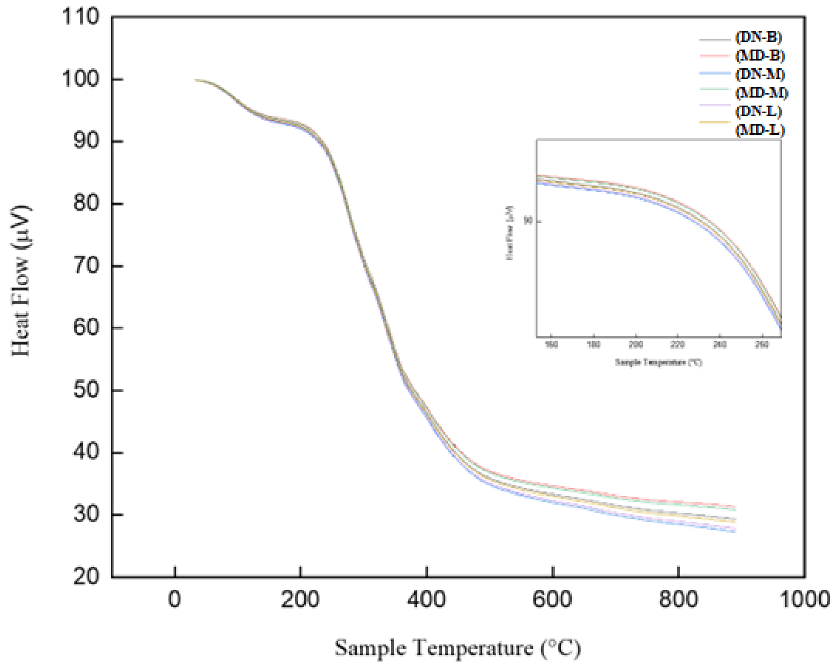


**Figure 4.6:** TGA of DPL.

# 4.3 Composite Material Results (Gypsum/DPL)

## 4.3.1 Density & Porosity properties

In the constructional sector, the utilization of lightweight materials is highly embraced due to their economic advantages [145], due their potential to uphold stability, stiffness, and durability [146, 147]. The density of the examined G-DPL composites was determined utilizing the five-weighing method. The margin of error in the calculations was below 2%. The third figure depicts the variations in absolute and apparent densities, as well as the total porosity of the G-DPL material about different sizes and mass fractions. Table 3 provides a summary of the densities and total porosity found in both the current study and literature. It was evident that the inclusion of DPL lightens mortars and leads to a reduction in density up to 13%.

The lightness of the tested compositions can be ascribed to the alveolar arrangement of DPL and its porous nature. The inclusion of DPL, whether in terms of weight or size, results in a rise in the porosity of the mixtures. Gypsum mortars that contains DPL at various fibre sizes demonstrates higher porosity in comparison to pure gypsum [73, 115]. This could be attributed to the formation of voids at the interfacial areas between the DPL and the gypsum matrix. The obtained outcome concurs with relevant literature [148, 149], according to which the introduction of DPL into the matrix amplifies the degree of air entrapment. The variability in porosity values can be attributed to the proportion and dimensions of DPL. Furthermore, the porosity was influenced by the proportion and particle size of DPL, as well as its distribution within the gypsum matrix. Chikhi [113] elaborated upon a similar trend.

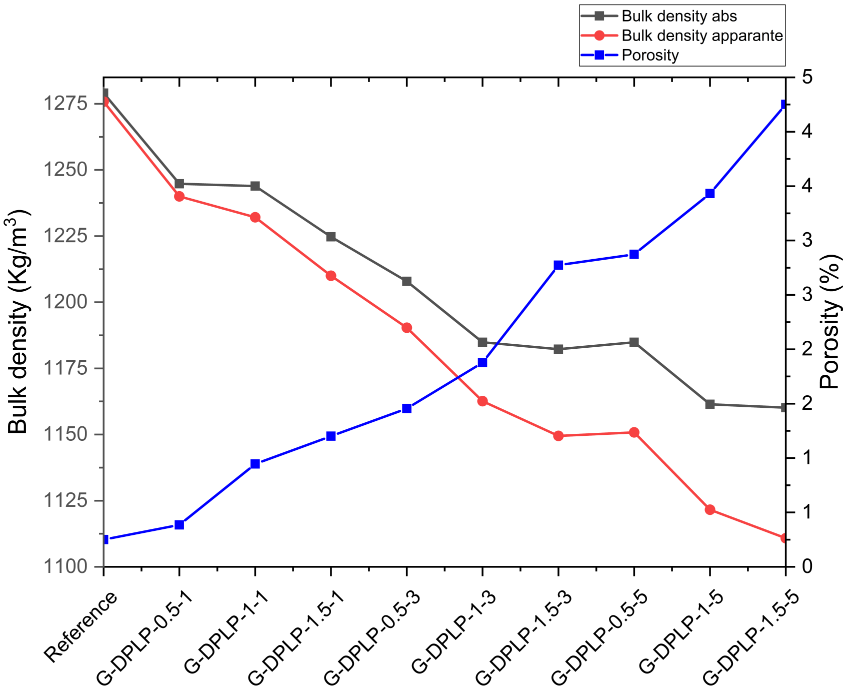


**Figure 4.7:** The density and porosity of the samples.

## 4.3.2 Water absorption

The water resistance of composites plays a crucial role, particularly when natural fibers are utilized. Various factors influence how composite materials absorb water, including temperature, additives volume fraction and type, area of exposed surfaces, interfacial bonding, diffusivity, reaction between water and matrix, surface protection, voids, and hydrophobic chains of the matrix [150, 151]. Based on Figure 4.8, it was evident that water absorption increased over time, and all the curves exhibited a similar pattern. Additionally, the reference mortar (with no DPL addition) had a lower adsorption rate compared to all other compositions.

A noteworthy observation was that water absorption primarily occurs during the initial stages of immersion, with a substantial quantity being absorbed within the first twenty seconds [152]. The absorption process was largely influenced by the open porosity of the material. The introduction of DPL led to the formation of numerous pores [153, 154]. It was widely acknowledged that lingo-cellulosic materials have a hydrophilic nature due to the presence of cellulose, hemicellulose, lignin, and other factors that contribute to their moisture absorption from the surrounding atmosphere [88, 155, 156]. Furthermore, the utilization of DPL results in higher water absorption. Notably, the concentration of DPL has a greater impact on water absorption compared to variations in diameter.

Figure 4.9 shows the evolution of the water content of gypsum-based composites filled with three different mass fractions and three sizes of DPL on days 7, 14, and 28. It appears that the addition of DPL with these different sizes in gypsum induces an increase in water content (7.51 to 8.94%). For the same composition, there was a slight increase in water content between day 7 and day 14, and between day 14 and day 28, with an increase of (between 0.19 and 2.5) and (between 0.06 and 0.5) respectively. This increase was greater when DPL was added. These results indicate that the ab-sorption rate decreases with time, confirming the previous results showing that absorption takes place in the early stages. These results indicate that incorporating a small amount of DPF into gypsum enhances water absorption [157].

Figure 4.10 represents the water absorption of G-DPL composites after 28 days. From the results, it was observed that the porosity of the mortar led to a significant in-crease of the values. This was due to the addition of DPL and its hygroscopic physiognomy [112]. Chikhi et al. [112], stated that the water content of composites depends strongly on the DPL water absorption capacity. According to numerous authors, the absorption depends on the size, content, and chemical composition (cellulose) of the natural fibre [119, 158, 159].

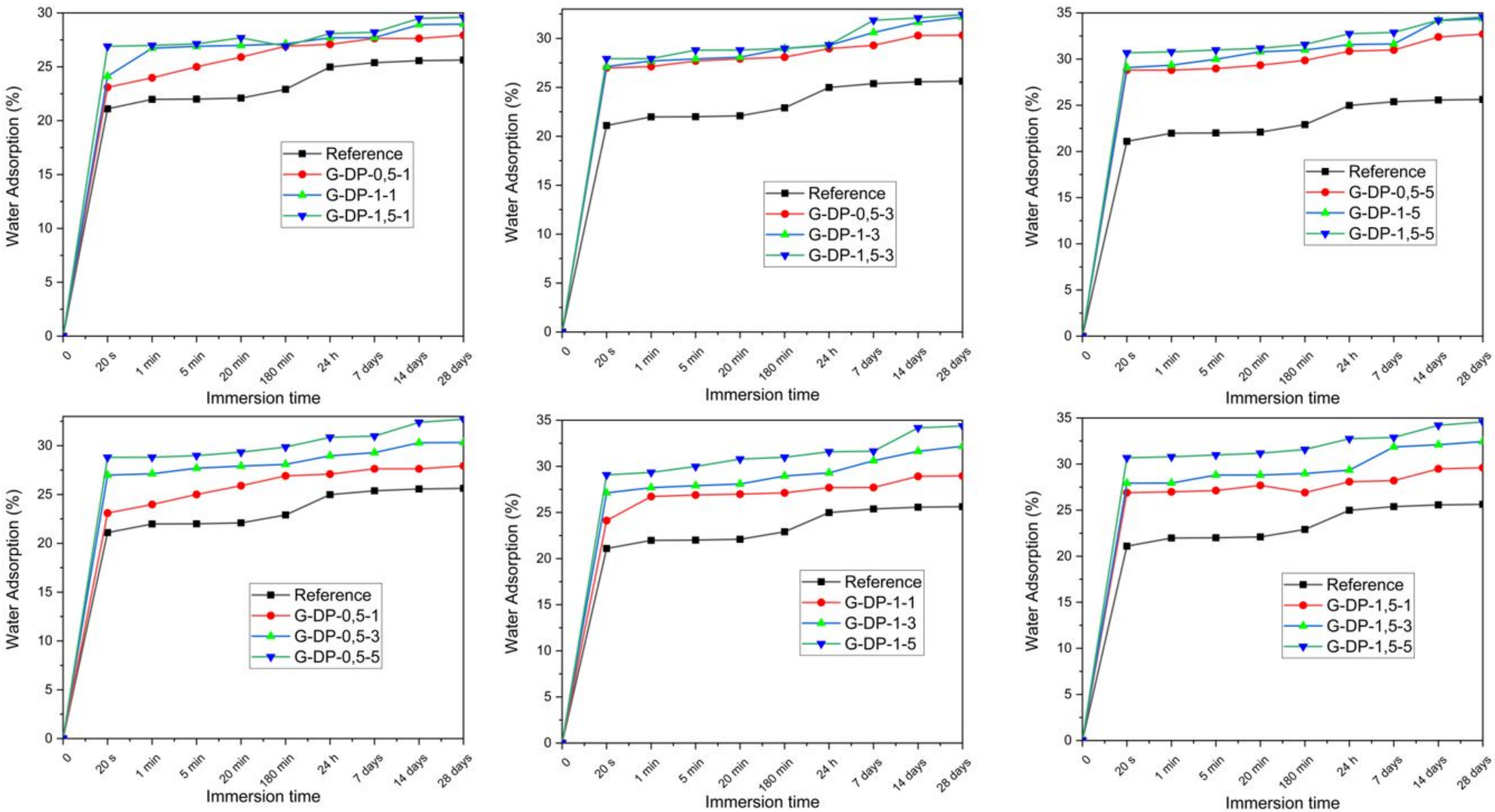


**Figure 4.8:** Water adsorption in the function of immersion time of composite samples.

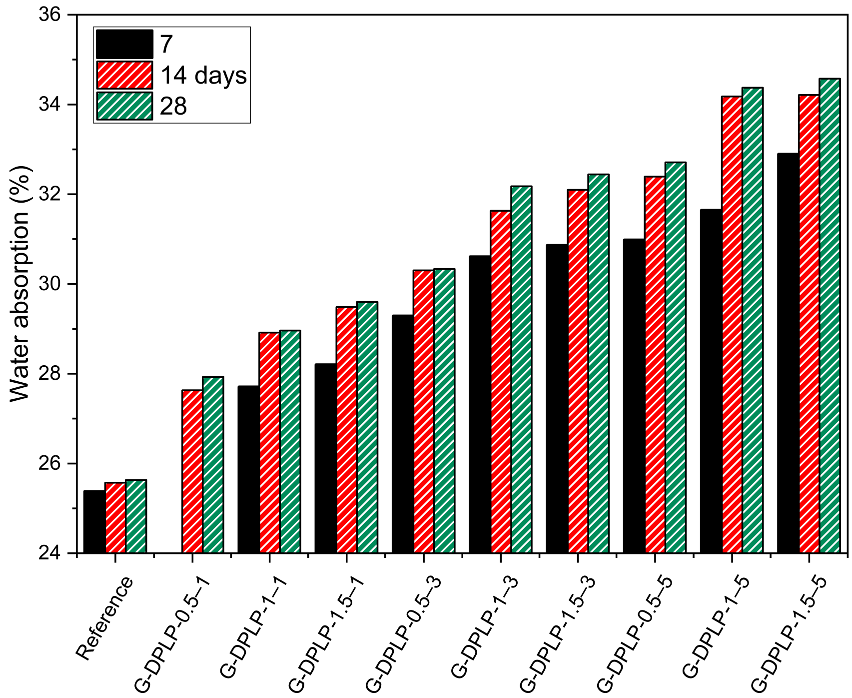


**Figure 4.9:** Water adsorption test after 7, 14, and 28 days of immersion of composite samples.

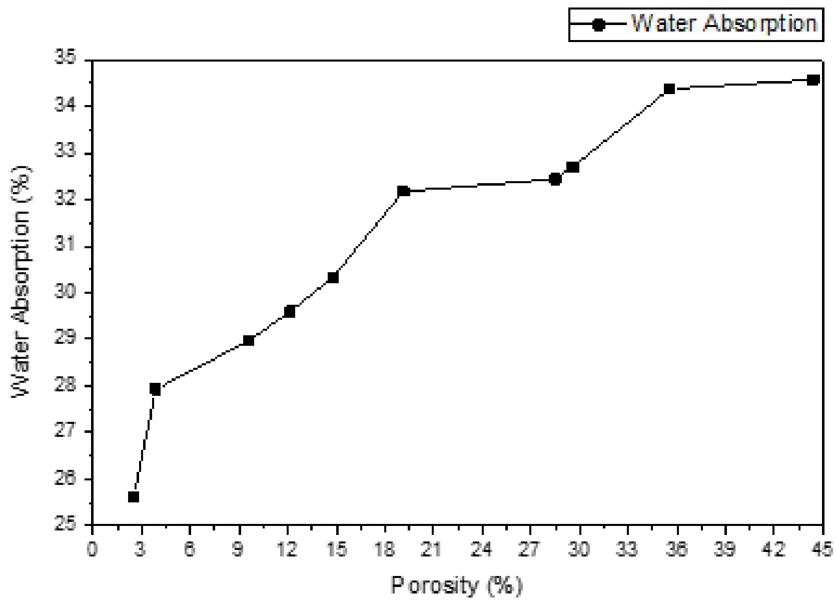


**Figure 4.10:** Correlation of water absorption with porosity of the compositions.

### 4.3.3 Mechanical properties

The addition of DPL into the compositions significantly impacts its mechanical behaviour, particularly in terms of flexural and compressive. Figure 8 depicts the flexural strength for all specimens at the age of 7, 14, and 28 days. The obtained outcomes reveal that flexural strength diminishes as the dimen-sions and concentration of DPL increases [117, 119]. A reduction of 25% in flexural strength was observed upon the inclusion of 1% DPL, followed by a declining fraction of decrease as the concentration or dimensions increase, within the range of (5.3 - 1.7%). Furthermore, a rise in flexural strength can be observed over time, specifically from 7 to 14 to 28 days. The reference composition showed a strength increase of 13% from 7 to 28d, which represents the most substantial elevation compared to the other com-positions (5 - 8%).

Figure 8 shows the compressive strength for all compositions at the age of 7, 14, and 28 days, which was decreased while increasing the dimension and concentration of DPL [41, 48]. A drop of 37% was shown when adding 3% of DPL and was fur-ther decreased (up to 50%) in a concentration of % of DPL. Over time, from 7 - 14 to 28 days, an increase in compressive strength can also be observed; an increase of 16% in the case of the reference mortar and an increase of 3 - 12% in the modified mortars. The latter variation depends on the proportion and particle size of DPL (decreases with the increase of concentration or dimension).

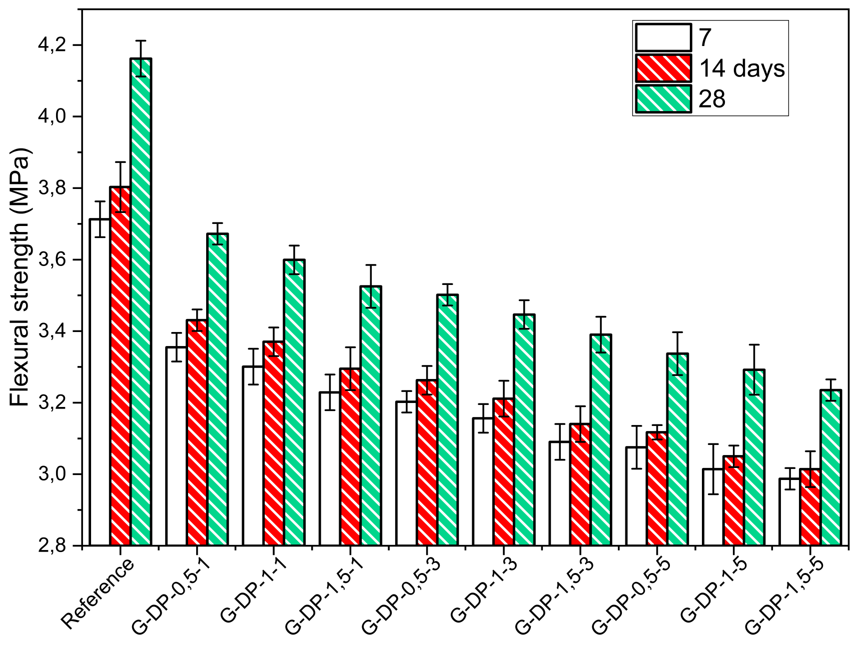


**Figure 4.11:** Flexural strength results of tested composites after (7, 14, and 28 days).

### 4.3.4 Thermal conductivity

Thermal conductivity represents a crucial characteristic within the domain of thermal insulation materials. This particular property is predicated upon a multitude of factors, including the morphology, density, and homogeneity of materials [155]. The thermal

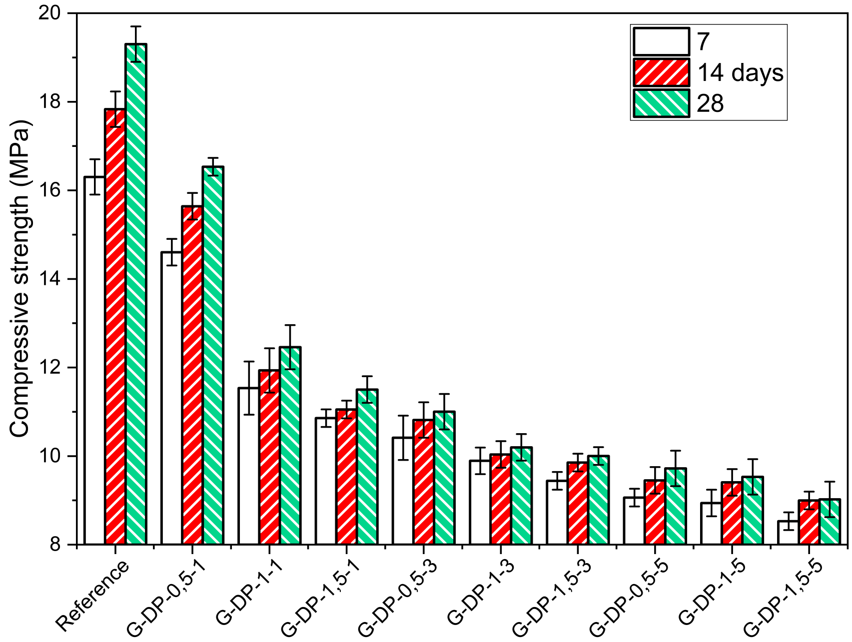


**Figure 4.12:** Compression strength results of tested composites after (7, 14, and 28 days).

conductivity's variation, correlated with the porosity of the compositions, is illustrated in Figures 9 and 10. This variation was examined for three different DPL sizes and concentration. The utilization of gypsum either in isolation or in conjunction with other materials enhances insulation due to its notably low thermal conductivity, which amounts to 0.8 $W/m.K$ in the context of our study [160].

Over 28 days, the thermal conductivity diminishes as the dosage of DPL increases. Moreover, it decreases in tandem with the rise in porosity rate and was inversely proportional to the voids that generated by DPL presence [161]. The relationship be-tween thermal conductivity and DPL was closely intertwined. Consequently, as the quantity of DPL increases, thermal conductivity experiences a decline [156, 162, 163].

In the present study, when adding 1% of DPL, thermal conductivity decreased around 22%, compared to the reference mortar, representing the most significant change. With each increase in DPL concentration or size, leading to a respective po-rosity rise, thermal conductivity was decreased. The recorded decrease ranges from 2 - 14%. Experimental results demonstrate that the thermal insulation effectiveness of the material was inversely related to its density [73]. These findings highlight the potential for producing insulation materials modified with DPL.

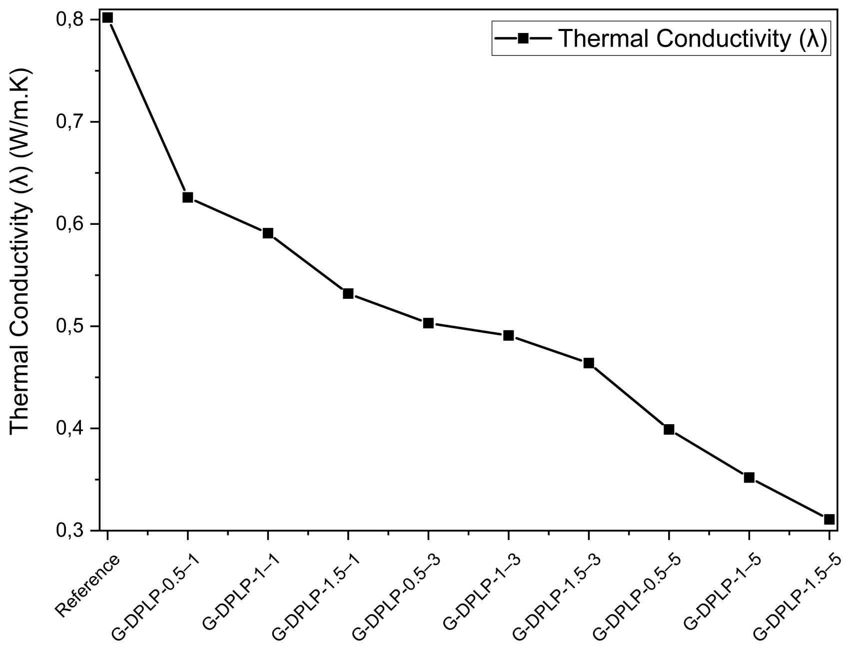


**Figure 4.13:** Evolution of the thermal conductivity of tested composites.

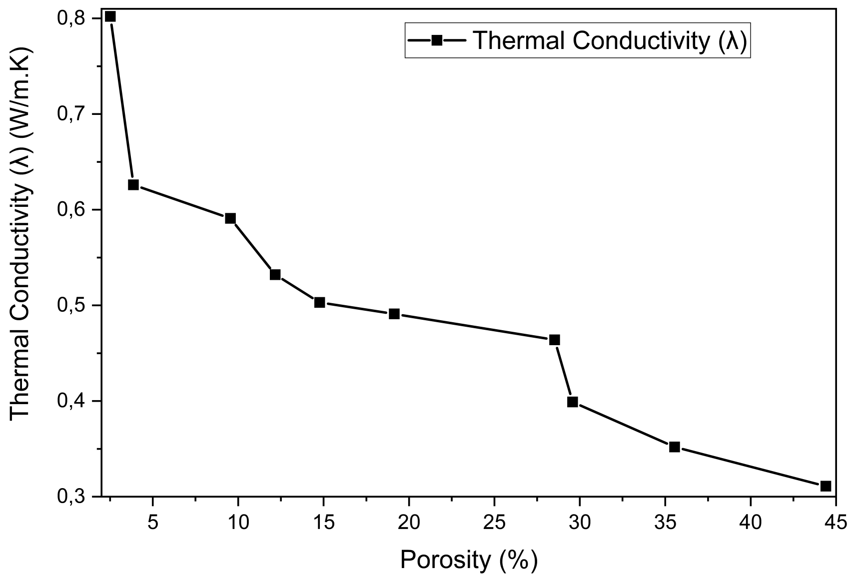


**Figure 4.14:** Correlation of thermal conductivity with the porosity of the material studied.

## 4.4 Discussions

This thesis focuses on the evaluation of two essential points; (i) the physical, chemical and thermal characterization of DPL, (ii) the exploitation of DPL as reinforcement in construction materials and studying their characteristics, properties and fireability as a reinforcement material for green composites applied in building constructions. DPL as a raw material, renewable and available in particular in Algeria shows its potential for use thanks to its characteristics and properties.

The results obtained through the various analyses and tests evaluating the physical, chemical and thermal characterization of DPL are directly and indirectly related to themselves and are corroborated by the preliminary results presented in the literature. According to the experimental results, DPL is characterized by its lightness, porosity, the presence of cellulose, hemicelluloses and lignin, and its good thermal stability. Knowing that DPL is an organic material, it is also characterized by properties that make it a reinforcing material for green composites.

After analyzing the physical, chemical and thermal characterizations of DPL and its potential to be a reinforcing material. An elaboration of a composite of gypsum and DPL with different concentration and dimension of DPL to study the characterizations of the green composite and its fireability. According to the experimental results, porosity was the parameter that most influenced the physical, mechanical and thermal properties of the mortars tested. The addition of DPL can modify the porosity of gypsum mortars, depending on its proportion and particle size. An increase in porosity gives the material a degree of lightness, favorable to specific applications (i.e. coatings and plasters). The addition of DPL can improve the lightness, mechanical properties, absorption and of course its thermal performance. To this extent, DPL can be used to produce sustainable green composites. To this extent, DPL can be used to produce durable mortars with elaborate properties, following the diachronic construction principles of Algeria and the MENA region.

# Chapter 5

# Conclusions and Recommendations

### Summary



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## 5.1 General conclusion

This final chapter synthesizes the results obtained during this thesis and, based on previous studies, provides practical recommendations for the use of construction materials derived from date palm waste. Future research directions in this field are also outlined. Throughout this thesis, the investigations have demonstrated the properties, performance, and challenges of utilizing date palm waste as a sustainable material in construction.

The research conducted under the thesis titled "Energetical Recovery of Biowaste Applied to Buildings in Algeria" has revealed innovative solutions that address the intersection of waste management and renewable energy in the Algerian context. The study extensively examined biowaste-to-energy conversion technologies and their applicability in the construction sector, highlighting the potential of biowaste to mitigate waste management issues while meeting the growing energy demands of buildings.

The findings emphasize the feasibility of integrating biowaste-based energy recovery systems into construction practices in Algeria. Environmental, economic, and social dimensions were scrutinized, revealing benefits such as reduced waste burdens, decreased greenhouse gas emissions, and improved energy efficiency. Specific focus was given to date palm fibers combined with gypsum, which demonstrated significant sustainability, energy efficiency, and structural suitability in various tests and analyses.

This research not only contributes to the academic understanding of sustainable building materials but also offers actionable strategies for policymakers and practitioners to adopt ecologically responsible approaches. The recommendations provided address technical, economic, social, and environmental constraints, paving the way for the broader application of biowaste in construction.

As the challenges of climate change and resource depletion persist, this thesis underscores the importance of adopting circular economy principles in the construction sector. The lessons learned and insights gained advocate for the harmonious integration of waste valorization and energy recovery, promoting sustainable development in Algeria and beyond. This thesis not only provides a comprehensive overview of the experimental data but also contextualizes these findings within the broader spectrum of sustainable construction practices and biowaste utilization. This culmination of research offers significant contributions to the field of sustainable building materials, paving the way for future innovations and applications in Algeria and beyond.

In conclusion, this chapter consolidates the findings and interprets their implications within the broader context of sustainable construction and biowaste utilization. Recommendations for optimizing the use of the studied material are presented alongside suggestions for future research. These recommendations aim to deepen knowledge and broaden the scope of biowaste applications, providing a foundation for continued innovation and progress in the field.

## 5.2 Recomandations and future work

The exploration of biowaste as a sustainable energy source presents a promising avenue for Algeria, offering not only an opportunity to address waste management challenges but also to enhance energy security and support environmental sustainability. The potential for biowaste-derived energy to contribute significantly to the country's energy mix, particularly in the building sector, necessitates a comprehensive approach encompassing assessment, innovation, and integration. To harness this potential fully, the following recommendations have been formulated. These recommendations aim to guide the strategic implementation of biowaste-to-energy solutions across the country, ensuring that efforts are both effective and aligned with Algeria's broader sustainability goals. The following recommendations and directions for future work are proposed to guide efforts in this domain:

1. Local Biowaste Assessment:

- Conduct comprehensive regional surveys to catalog biowaste types and quantities.
- Evaluate the energy potential of available resources and address logistical considerations for collection and processing.

2. Technology Adaptation and Innovation:

   - Contextually adapt advanced biowaste-to-energy technologies, such as anaerobic digestion, pyrolysis, and gasification.
   - Focus on enhancing process efficiencies, reducing costs, and minimizing environmental impacts through research on novel catalysts and optimized reaction conditions.

3. Sustainability and Environmental Impact:

   - Perform Life Cycle Assessments (LCA) to evaluate the environmental footprint of biowaste-to-energy processes.
   - Develop strategies to mitigate negative impacts, such as greenhouse gas emissions, and ensure compliance with environmental standards.

4. Integration with Building Infrastructure:

   - Assess the feasibility of integrating biowaste-derived energy into existing and new buildings.
   - Explore energy storage solutions, distribution systems, and retrofitting options to foster energy-efficient, smart buildings.

5. Policy and Regulatory Framework:

   - Advocate for supportive policies and incentives for biowaste energy projects.
   - Establish clear guidelines for biowaste management to create an investment-friendly environment.

6. Public Awareness and Education:

- Launch outreach programs and community engagement initiatives to raise awareness about biowaste energy recovery.
- Promote public participation through educational campaigns.

7. Collaboration with Industry and Academia:

   - Strengthen partnerships among industry players, academic institutions, and government agencies.
   - Facilitate joint research projects, technology transfer agreements, and pilot programs.

8. Pilot Projects and Case Studies:

   - Implement pilot projects across different regions to demonstrate the practicality and benefits of biowaste-to-energy initiatives.
   - Document case studies to develop best practices and guide broader implementation.

9. Scalability and Economic Viability:

   - Conduct market analyses, feasibility studies, and develop business models to ensure financial sustainability.
   - Explore commercialization strategies and address barriers to market entry.

10. Customization to Local Conditions:

    - Tailor technologies and solutions to Algeria's specific climatic, cultural, and logistical contexts.
    - Optimize processes for locally available biowaste characteristics.

As we consider the trajectory of biowaste energy recovery and its application within the Algerian context, it becomes evident that while substantial strides have been made, there remains a vast landscape of untapped potential and unanswered questions. The journey thus far has illuminated the viability and transformative power of biowaste as a sustainable energy source, yet it has also underscored the complexity of its integration into existing energy systems, building materials, and broader societal frameworks. Recognizing these challenges and opportunities, the following suggestions for future work are proposed to extend the boundaries of current knowledge and practice in biowaste utilization. These suggestions aim to address the critical areas of technology, integration, innovation, and sustainability, laying the groundwork for a future where biowaste energy recovery is a cornerstone of Algeria's energy and environmental strategy.

1. Advancing Biowaste Conversion Technologies:
    - Research innovative technologies, focusing on process efficiencies, cost reduction, and environmental sustainability.
    - Develop sustainable and efficient process models, incorporating hybrid systems that integrate biowaste with other renewable energy sources, such as solar and wind.
2. Sustainable Building Materials:
    - Investigate the potential of biowaste in creating composite and insulation materials.
    - Study the acoustice insolation, recycability, and durability properties of these materials for use in energy-efficient buildings.
3. Comprehensive Life Cycle Assessment:
    - Conduct in-depth LCA of biowaste-to-energy processes, from collection to usage, to quantify environmental impacts and guide decision-making.
4. Economic Analysis and Commercialization:
    - Perform detailed economic analyses to evaluate market demands, cost-benefit scenarios, and commercialization pathways.
    - Address economic barriers and explore strategies for fostering investment.
5. Social Dimensions and Community Engagement:
    - Study community attitudes toward biowaste energy and develop effective participation models.

- Explore the social and economic impacts of biowaste energy projects on local communities.

6. Climate Resilience and Adaptation:

   - Investigate how biowaste-derived energy and materials can enhance climate resilience and reduce carbon footprints.

   - Tailor solutions to Algeria's climate conditions to maximize adaptation benefits.

In conclusion, the recommendations and future work outlined above present a roadmap for leveraging biowaste as a cornerstone of Algeria's energy and environmental strategy. By addressing technological, economic, social, and environmental aspects, Algeria can unlock the transformative potential of biowaste, paving the way for a sustainable and resilient energy future.

# References


[1] Silpa; Kaza, Lisa C.; Yao, Perinaz; Bhada-Tata, and Frank Van Woerden. *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050.* Washington, DC: World Bank, 2018. 2

[2] Sana Ben-Othman, Ivi Jõudu, and Rajeev Bhat. *Bioactives from Agri-Food Wastes : Present Insights.* 2020. 2

[3] M. R. Kosseva. *Management and Processing of Food Wastes*, **6**. Elsevier B.V., second edi edition, 2011. 2, 5

[4] Poonam Sharma, Vivek Kumar Gaur, Sang Hyoun Kim, and Ashok Pandey. **Microbial strategies for bio-transforming food waste into resources**. *Bioresource Technology*, **299**(December 2019):122580, 2020. 2

[5] Mehdi Jonoobi, Masoud Shafie, Younes Shirmohammadli, Alireza Ashori, Hamid Zarea-Hosseinabadi, and Tizazu Mekonnen. **A review on date palm tree: Properties, characterization and its potential applications**. *Journal of Renewable Materials*, **7**(11):1055–1075, 2019. 2, 15, 45

[6] Said Awad, Yonghui Zhou, Evina Katsou, Yunfeng Li, and Mizi Fan. *A Critical Review on Date Palm Tree (Phoenix dactylifera L.) Fibres and Their Uses in Bio-composites*. Number 0123456789. Springer Netherlands, 2020. 2, 15, 18, 19, 31

[7] Midani. Mohamed, Naheed. Saba, and Othman Y. Alothman. *Date Palm Fiber Composites.* Springer Nature Singapore Pte Ltd., 2020. 2, 3, 13, 14, 15, 21

[8] Ahmad Alawar, Ahmad M. Hamed, and Khalifa Al-Kaabi. **Characterization of treated date palm tree fiber as composite reinforcement**. *Composites Part B: Engineering*, **40**(7):601–606, 2009. 2, 15, 21, 22

[9] M. Siti Alwani, H. P.S.Abdul Khalil, M. Asniza, S. S. Suhaily, A. S.Nur Amiranajwa, and M. Jawaid. *Biomass and Bioenergy: Processing and Properties*, **9783319076**. 2014. 2

[10] Haithem Boumediri, Abderrezak Bezazi, Gilberto Garcia Del Pino, Abdelkrim Haddad, Fabrizio Scarpa, and Alain Dufresne. **Extraction and characterization of vascular bundle and fiber strand from date palm rachis as potential bio-reinforcement in composite**. *Carbohydrate Polymers*, **222**(April):114997, 2019. 2, 18, 19, 47, 48, 50

[11] Abderrezak Bezazi, Haithem Boumediri, Gilberto Garcia del Pino, Boudjema Bezzazi, Fabrizio Scarpa, Paulo N.B. Reis, and Alain Dufresne. **Alkali Treatment Effect on Physicochemical and Tensile Properties of Date Palm Rachis Fibers**. *Journal of Natural Fibers*, **00**(00):1–18, 2020. 2, 18, 19, 49, 50

[12] Oum Kelthoum Laghouiter, Mohamed Benalia, Nadhir Gourine, Amar Djeridane, Isabelle Bombarda, and Mohamed Yousfi. **Chemical characterization and in vitro antioxidant capacity of nine Algerian date palm cultivars (Phoenix dactylifera L.) seed oil**. *Mediterranean Journal of Nutrition and Metabolism*, **11**(2):103–117, 2018. 3

[13] Kenza Almi, Adel Benchabane, Said Lakel, and Abdelouahed Kriker. **Potential utilization of date palm wood as composite reinforcement**. *Journal of Reinforced Plastics and Composites*, **34**(15):1231–1240, 2015. 3, 17, 18, 19, 21, 22, 45, 48

[14] Boudjemaa Agoudjil, Adel Benchabane, Abderrahim Boudenne, Laurent Ibos, and Magali Fois. **Renewable materials to reduce building heat loss: Characterization of date palm wood**. *Energy and Buildings*, **43**(2-3):491–497, 2011. 3, 14, 15, 17, 18, 21, 22, 44, 47, 48

[15] Fabrizo Scarpa, Salah Amroune, and Abderrezak Bezazi. **Statistical analysis and effect of chemical treatment on the physico- mechanical behavior of fibres from date-palm fruit branches**. *Synthèse : Revue des Sciences et de la Technologie*, **120**(31):108–120, 2015. 3, 18

[16] Navarro Ferronato and Vincenzo Torretta. **Waste mismanagement in developing countries: A review of global issues**. *International Journal of Environmental Research and Public Health*, **16**(6), 2019. 4

[17] Samuel Asumadu Sarkodie and Phebe Asantewaa Owusu. **Impact of COVID-19 pandemic on waste management**. *Environment, Development and Sustainability*, **23**(5):7951–7960, 2021. 4

[18] Richard Sikkema, Martin Junginger, Wilfried Pichler, Sandra Hayes, and André P.C. Faaij. **The international logistics of wood pellets for heating and power production in Europe: Costs, energy-input and greenhouse gas balances of pellet consumption in Italy, Sweden and the Netherlands**. *Biofuels, Bioproducts and Biorefining*, **4**(2):132–153, 2010. 6

[19] Virginia H. Dale, Keith L. Kline, Esther S. Parish, Annette L. Cowie, Robert Emory, Robert W. Malmsheimer, Raphael Slade, Charles Tattersall Tat Smith, Thomas Bently BEN Wigley, Niclas S. Bentsen, Göran Berndes, Pierre Bernier, Miguel Brandão, Helena L. Chum, Rocio Diaz-Chavez, Gustaf Egnell, Leif Gustavsson, Jörg Schweinle, Inge Stupak, Paul Trianosky, Arnaldo Walter, Carly Whittaker, Mark Brown, George Chescheir, Ioannis Dimitriou, Caspar Donnison, Alison Goss Eng, Kevin P. Hoyt, Jennifer C. Jenkins, Kristen Johnson, Charles A. Levesque, Victoria Lockhart, Maria Cristina Negri, Jami E. Nettles, and Maria Wellisch. **Status and prospects for renewable energy using wood pellets from the southeastern United States**. *GCB Bioenergy*, **9**(8):1296–1305, 2017. 6

[20] Lee R. Lynd, Eric Larson, Nathanael Greene, Mark Laser, John Sheehan, Bruce E. Dale, Samuel McLaughlin, and Michael Wang. **The role of biomass in America's energy future: Framing the analysis**. *Biofuels, Bioproducts and Biorefining*, **3**(2):113–123, 2009. 6

[21] Nimisha Tripathi, Colin D. Hills, Raj S. Singh, and Christopher J. Atkinson. **Biomass waste utilisation in low-carbon products: harnessing a major potential resource**. *npj Climate and Atmospheric Science*, **2**(1), 2019. 6

[22] Elie Awwad, Mounir Mabsout, Bilal Hamad, and Helmi Khatib. **PRELIMINARY STUDIES ON THE USE OF NATURAL FIBERS IN SUSTAINABLE CONCRETE**. *Lebanese Science Journal*, **12**(1):154–169, 2010. 6

[23] Mohamed Aymen Kethiri and Mourad Chikhi. **A thermophysical investigation of the potential for the use of wastepaper for insulation building materials**. *International Wood Products Journal*, pages 1–9, 2024. 6, 23

[24] A Naaman and M Harajli. **A State-of-the-Art Report on âĂIJMechanical Properties of High Performance Fiber Concrete,âĂİ**. *University of Michigan, USA*, 1990. 6

[25] Loutfy I. El-Juhany. **Degradation of Date Palm Trees and Date Production in Arab Countries: Causes and Potential Rehabilitation**. *Australian Journal of Basic and Applied Sciences*, **4**(8):3998–4010, 2010. 6, 15, 17

[26] Abeer I Alwared, Suhair K A Al-hubboubi, and Daad Saad Dawood. **Effect of Date Palm Leaf Fiber on Mechanical Properties of Concrete**. (March):49–66, 2016. 6, 39

[27] Faesal Alatshan, Abdelmajeed Mohammed Altlomate1, Fidelis Mashiri, and Wesam Alamin. **Effect of date palm fibers on the mechanical properties of concrete**. **8**:37–41, 2017. 6, 39

[28] Negina Aminova and Karol S. Sikora. **Effects of Date Palm Fibres on the Properties of Concrete**. *Chemical Engineering Transactions*, **94**(May):1171–1176, 2022. 6

[29] Mohamed Aymen Kethiri, Noureddine Belghar, Mourad Chikhi, Yousra Boutera, and Charafeddine Beldjani. **Experimental Study on the Effect of Date Palm Powder on the Thermal and Physico-Mechanical Properties of Gypsum Mortars**. *Sustainability (Switzerland)*, **16**(7):1–15, 2024. 6, 27

[30] H. Savastano, P. G. Warden, and R. S.P. Coutts. **Brazilian waste fibres as reinforcement for cement-based composites**. *Cement and Concrete Composites*, **22**(5):379–384, 2000. 6

[31] V. Agopyan, H. Savastano, V. M. John, and M. A. Cincotto. **Developments on vegetable fibre-cement based materials in São Paulo, Brazil: An overview**. *Cement and Concrete Composites*, **27**(5):527–536, 2005. 6

[32] D V Johnson. **Introduction: Date Palm Biotechnology**. In S M Jain and J M Al-Khayri, editors, *Date Palm Biotechnology*. Springer, Netherlands, 2011. 13

[33] A Dakheel. **The date palm from traditional resource to green wealth**. *Emirates Centre for Strategic Studies and Research, Abu Dhabi*, pages 199–211, 2003. 13, 30

[34] Faris M. AL-Oqla, Othman Y. Alothman, M. Jawaid, S. M. Sapuan, and M. H. Es-Saheb. **Processing and Properties of Date Palm Fibers and Its Composites**. In *Biomass and Bioenergy*, **9783319076**, pages 1–367. 2014. 14, 15, 17, 21, 22, 23, 30, 46

[35] Basheer A Alshammari, Naheed Saba, Majed D Alotaibi, Mohammed F Alotibi, Mohammad Jawaid, and Othman Y Alothman. **Evaluation of Mechanical, Physical, and Morphological Properties of Epoxy Composites Reinforced with Different Date Palm Fillers**. *Materials*, 2019. 14, 19, 25

[36] Amira Najahi, Quim Tarrés, Pere Mutjé, Marc Delgado-Aguilar, Jean Luc Putaux, and Sami Boufi. **Lignin-Containing Cellulose Nanofibrils from TEMPO-Mediated Oxidation of Date Palm Waste: Preparation, Characterization, and Reinforcing Potential**. *Nanomaterials*, **13**(1), 2023. 15

[37] Musa Adamu, Fayez Alanazi, Yasser E. Ibrahim, Hani Alanazi, and Veerendrakumar C. Khed. **A Comprehensive Review on Sustainable Natural Fiber in Cementitious Composites: The Date Palm Fiber Case**. *Sustainability (Switzerland)*, **14**(11):1–31, 2022. 15

[38] A Jaradat and A Zaid. **Quality Traits of Date Palm Fruits in a Center of Origin and Center of Diversity**. *Journal of Food, Agriculture Environment*, **2**:208–217, 2004. 15

[39] Lobna A Elseify, Mohamad Midani, Tamer Hamouda, and Ahmed Hassanin. **Novel Textile Fibers From Date Palm Byproducts : Palmfil**. (May):28–30, 2021. 15, 17, 50

[40] A A Kader and A M Hussein. **Harvesting and Post-harvest handling of dates**. International Center for Agricultural Research in the Dry Areas (ICARDA), 2009. 15

[41] Basim Abu-Jdayil, Abdel Hamid I. Mourad, Atif Hussain, and Hyder Al Abdallah. **Thermal insulation and mechanical characteristics of polyester filled with date seed wastes**. *Construction and Building Materials*, **315**(May 2021):125805, 2022. 15, 21, 57

[42] Food and Agriculture Organization of the United Nations. **Date Palm Production and Cultivation**. `https://www.fao.org/home/en/`, 2023. 15, 17

[43] Moufida Beroual, Djalal Trache, Oussama Mehelli, Lokmane Boumaza, Ahmed Fouzi Tarchoun, Mehdi Derradji, and Kamel Khimeche. **Effect of the Delignification Process on the Physicochemical Properties and Thermal Stability of Microcrystalline Cellulose Extracted**

**from Date Palm Fronds**. *Waste and Biomass Valorization*, (0123456789), 2020. 17, 18

[44] Abdelhak Kareche, Boudjemaa Agoudjil, Bourhaneddine Haba, and Abderrahim Boudenne. **Study on the Durability of New Construction Materials Based on Mortar Reinforced with Date Palm Fibers Wastes**. *Waste and Biomass Valorization*, **11**(7):3801–3809, 2020. 17, 27

[45] Abderrezak Bezazi, Salah Amroune, Fabrizio Scarpa, Alain Dufresne, and Abdellatif Imad. **Investigation of the for green composites reinforcement: Quasi-static and fatigue characterization of the fiber**. *Industrial Crops and Products*, **146**(January):112135, 2020. 17, 49, 50

[46] Abdelhafid Akhzeroun, Abdelaziz Semcha, Abderrezak Bezazi, Haithem Boumediri, Paulo N.B. Reis, and Fabrizio Scarpa. **Development and characterization of a new sustainable composite reinforced with date palm stems for rehabilitation and reconstruction of earthen built heritage**. *Composite Structures*, **316**(April):117015, 2023. 17, 18

[47] Faleh A Al-sulaiman. **Mechanical Properties of Date Palm Fiber Reinforced Composites**. *Applied Composite Materials*, **9**:369–377, 2002. 17

[48] R. Belakroum, A. Gherfi, M. Kadja, C. Maalouf, M. Lachi, N. El Wakil, and T. H. Mai. **Design and properties of a new sustainable construction material based on date palm fibers and lime**. *Construction and Building Materials*, **184**:330–343, 2018. 17, 18, 27, 57

[49] Nawal Chennouf, Boudjemma Agoudjil, Abderrahim Boudenne, Karim Benzarti, and Fathi Bouras. **Hygrothermal characterization of a new bio-based construction material: Concrete reinforced with date palm fibers**. *Construction and Building Materials*, **192**(July):348–356, 2018. 17, 18, 27

[50] Loutfy I. El-Juhany. **Surveying of lignocellulosic agricultural residues in some major cities of Saudi Arabia**. Research Bulletin 1, Agricultural Research Center, College of Agriculture, King Saud University, Saudi Arabia, 2001. 17

[51] Faris M AL-Oqla and S M Sapuan. **Natural fiber reinforced polymer composites in industrial applications : feasibility of date palm fi bers for sustainable automotive industry**. *Journal of Cleaner Production*, pages 1–8, 2014. 17, 22

[52] Ebrahim Taban, Ali Khavanin, Ahmad Jonidi Jafari, Mohammad Faridan, and Ali Kazemi Tabrizi. **Experimental and mathematical survey of sound absorption performance of date palm fibers**. *Heliyon*, **5**(6):e01977, 2019. 18

[53] Ebrahim Taban, Ali Khavanin, Abdolreza Ohadi, Azma Putra, Ahmad Jonidi Jafari, Mohammad Faridan, and Ardalan Soleimanian. **Study on the acoustic characteristics of natural date palm fibres: Experimental and theoretical approaches**. *Building and Environment*, **161**(July):106274, 2019. 18

[54] Lobna A Elseify, Mohamad Midani, Lamia Ahmed Shihata, and Hamed El-Mously. **Review on cellulosic fibers extracted from date palms (Phoenix Dactylifera L.) and their applications**. *Cellulose*, **26**:2209–2232, 2019. 18

[55] E A Darwish and Ayman Moustafa. **Developing a Novel Prefabricated Enclosure Wall Panel based on the Traditional Technical Heritage in Egypt**. (January), 2024. 18

[56] S. O. Bamaga. **A Review on the Utilization of Date Palm Fibers as Inclusion in Concrete and Mortar**. *Fibers*, **10**(4), 2022. 18

[57] Youcef Bellatrache, Layella Ziyani, Anne Dony, Mohamed Taki, and Smail Haddadi. **Effects of the addition of date palm fibers on the physical, rheological and thermal properties of bitumen**. *Construction and Building Materials*, **239**:117808, 2020. 18

[58] M. A. Kethiri, M. Chikhi, C. Tedeschi, and N. Belghar. **The Characterization of the Date Palm Tree Leaflet for Using That as Green Materials for Building House**. *Materials Circular Economy*, **4**(1), 2022. 18, 34, 47, 48, 50

[59] Mohamed Aymen Kethiri, Noureddine Belghar, Mourad Chikhi, Amina Hachaichi, Charafeddine Beldjani, Yousra Boutera, and Cristina Tedeschi. **Physical , chemical , and thermal behaviour of date palm leaflet as potential reinforcement material for green composites**. *Biomass Conversion and Biorefinery*, (0123456789), 2024. 18, 19

[60] Mohamad Alhijazi, Qasim Zeeshan, Babak Safaei, Mohammed Asmael, and Zhaoye Qin. **Recent Developments in Palm Fibers Composites: A Review**. *Journal of Polymers and the Environment*, **28**(12):3029–3054, 2020. 19, 21, 49

[61] Mohamed Hamdy Gheith, Mohamed Abdel Aziz, Waheedullah Ghori, Naheed Saba, Mohammad Asim, Mohammad Jawaid, and Othman Y. Alothman. **Flexural, thermal and dynamic mechanical properties of date palm fibres reinforced epoxy composites**. *Journal of Materials Research and Technology*, **8**(1):853–860, 2019. 19, 23

[62] Sabrine Hamza, Houda Saad, Bertrand Charrier, Naceur Ayed, and Fatima Charrier-el Bouhtoury. **Physico-chemical characterization of Tunisian plant fibers and its utilization as reinforcement for plaster based composites**. *Industrial Crops Products*, **49**:357–365, 2013. 19, 21

[63] Ramadan A. Nasser and Hamad A. Al-Mefarrej. **Midribs of date palm as a raw material for wood-cement composite industry in Saudi Arabia**. *World Applied Sciences Journal*, **15**(12):1651–1658, 2011. 19, 27

[64] Nedal Y. Abu-Thabit, Ahmed Abu Judeh, Abbas S. Hakeem, Anwar Ul-Hamid, Yunusa Umar, and Ayman Ahmad. **Isolation and characterization of microcrystalline cellulose from date seeds (Phoenix dactylifera L.)**. *International Journal of Biological Macromolecules*, **155**:730–739, 2020. 19

[65] Abdelkader Nabili, Arbi Fattoum, Raphaël Passas, Elimame Elaloui, and Abdelkader Nabili. **EXTRACTION AND CHARACTERIZATION OF CELLULOSE FROM DATE PALM SEEDS ( Phoenix dactylifera L .)**. *Cellulose Chemistry and Technology*, **50**:9–10, 2014. 19

[66] Dounia Derdour, Mourad Behim, and Mohammed Benzerara. **Effect of date palm and polypropylene fibers on the characteristics of self-compacting concrete: comparative study**. *Frattura ed Integrita Strutturale*, **17**(64):31–50, 2023. 19

[67] Othman Y. Alothman, Hamid M. Shaikh, Basheer A. Alshammari, and Mohammad Jawaid. **Structural, Morphological and Thermal Properties of Nano Filler Produced from Date Palm-Based Micro Fibers (Phoenix dactylifera L.)**. *Journal of Polymers and the Environment*, **30**(2):622–630, 2022. 19

[68] Nabila Saadaoui, Antoine Rouilly, Khalid Fares, and Luc Rigal. **Characterization of date palm lignocellulosic by-products and self-bonded composite materials obtained thereof**. *Materials and Design*, **50**:302–308, 2013. 19, 21

[69] Mustapha Boumhaout, Lahcen Boukhattem, Hassan Hamdi, and Brahim Benhamou. **Thermomechanical characterization of a bio-composite building material : Mortar reinforced with date palm fibers mesh**. *Construction and Building Materials*, **135**:241–250, 2017. 21, 22, 27

[70] Lahcen Boukhattem, Mustapha Boumhaout, Hassan Hamdi, and Brahim Benhamou. **Moisture content influence on the thermal conductivity of insulating building materials made from date palm fibers mesh**. *Construction and Building Materials*, **148**:811–823, 2017. 21, 22, 27

[71] Wail N. Al-Rifaie and Maamoon Al-Niami. **Mechanical performance of date palm fibre-reinforced gypsums**. *Innovative Infrastructure Solutions*, **1**(1), 2016. 21, 22, 27, 38

[72] Hom Dhakal, Alain Bourmaud, Francoise Berzin, Fahad Almansour, Zhongyi Zhang, Darshil U Shah, and Johnny Beaugrand. **Industrial Crops Products Mechanical properties of leaf sheath date palm fibre waste biomass reinforced polycaprolactone ( PCL ) biocomposites**. *Industrial Crops Products*, **126**(October):394–402, 2018. 21

[73] A. Djoudi, M.M. Khenfer, A. Bali, E.H. Kadri, and G. Debicki. **Performance of date palm fibres reinforced plaster concrete**. *International Journal of the Physical Sciences*, **7**(21):2845–2853, 2012. 21, 22, 52, 58

[74] Houssam Eddine Benchouia, Belhi Guerira, Mourad Chikhi, Hamida Boussehel, and Cristina Tedeschi. **An experimental evaluation of a new eco-friendly insulating material based on date palm fibers and polystyrene**. *Journal of Building Engineering*, **65**, apr 2023. 21, 22, 23

[75] Tarek Djoudi, Hocine Djemai, Mabrouk Hecini, and Ahmida Ferhat. **Physical, Thermal and Mechanical Characterization of a New Material Composite Based on Fibrous Wood Particles of Date Palm Tree**. *Revue des Composites et des Materiaux Avances*, **32**(1):45–52, 2022. 21, 22

[76] N Saba, Othman Y Alothman, Zeyad Almutairi, and M Jawaid. **Date palm reinforced epoxy composites: tensile, impact and morphological properties**. *Integrative Medicine Research*, (x x):1–11, 2019. 21, 22, 25

[77] F. Delzendehrooy, M R. Ayatollahi, and L F M. Silva. **Strength improvement of adhesively bonded single lap joints with date palm fibers: Effect of type, size, treatment method and density of fibers**. *Composites Part B*, page 107874, 2020. 21, 22

[78] ALMI Kenza. **Développement et caractérisation de matériaux à base du bois de palmier dattier adaptés aux applications de développement durable en Algérie**. 2018. 21

[79] P Noorunnisa Khanam and M A Almaadeed. **Improvement of ternary recycled polymer blend reinforced with date palm fibre**. *JOURNAL OF MATERIALSDESIGN*, **60**:532–539, 2014. 23, 24

[80] Alireza Dehghani, Sara Madadi, Mariam A Al-maadeed, Azman Hassan, and Mat Uzir. **Mechanical and thermal properties of date palm leaf fiber reinforced recycled poly ( ethylene terephthalate ) composites**. *JOURNAL OF MATERIALSDESIGN*, **52**:841–848, 2013. 23, 24, 50

[81] Abdalla Abdal-hay, Ngakan Putu, Gede Suardana, and Do Yeon Jung. **Effect of Diameters and Alkali Treatment on the Tensile Properties of Date Palm Fiber Reinforced Epoxy Composites**. **13**(7):1199–1206, 2012. 23

[82] Tahar Masri, Houdayfa Ounis, Lakhdar Sedira, Abdelhak Kaci, and Adel Benchabane. **Characterization of new composite material based on date palm leaflets and expanded polystyrene wastes**. *Construction and Building Materials*, **164**(January):410–418, 2018. 23

[83] Khadija M. Zadeh, I. M. Inuwa, Reza Arjmandi, Azman Hassan, M. Almaadeed, Zurina Mohamad, and P. Noorunnisa Khanam. **Effects of date palm leaf fiber on the thermal and tensile properties of recycled ternary polyolefin blend composites**. *Fibers and Polymers*, **18**(7):1330–1335, 2017. 23

[84] Mariam A Almaadeed, Ramazan Kahraman, P Noorunnisa Khanam, and Nabil Madi. **Date palm wood flour / glass fibre reinforced hybrid composites of recycled polypropylene : Mechanical and thermal properties**. *JOURNAL OF MATERIALSDESIGN*, **42**:289–294, 2012. 23, 24

[85] B. F. Abu-Sharkh and H. Hamid. **Degradation study of date palm fibre/polypropylene composites in natural and artificial weathering: Mechanical and thermal analysis**. *Polymer Degradation and Stability*, **85**(3 SPEC. ISS.):967–973, 2004. 24

[86] Hamdy Ibrahim, Mahmoud Farag, Hassan Megahed, and Sherif Mehanny. **Characteristics of starch-based biodegradable composites reinforced with date palm and flax fibers**. *Carbohydrate Polymers*, **101**(1):11–19, 2014. 24

[87] Seyed Mohammad Mirmehdi, Farhad Zeinaly, and Fatemeh Dabbagh. **Date palm wood flour as filler of linear low-density polyethylene**. *Composites Part B: Engineering*, **56**:137–141, 2014. 24

[88] Jyoti R. Mohanty, Sankar N. Das, Harish C. Das, and Sarat K. Swain. **Effect of chemically modified date palm leaf fiber on mechanical, thermal and rheological properties of polyvinylpyrrolidone**. *Fibers and Polymers*, **15**(5):1062–1070, 2014. 24, 53

[89] Hamdy Ibrahim, Sherif Mehanny, Lamis Darwish, and Mahmoud Farag. **A Comparative Study on the Mechanical and Biodegradation Characteristics of Starch-Based Composites Reinforced with Different Lignocellulosic Fibers**. *Journal of Polymers and the Environment*, **26**(6):2434–2447, 2018. 24

[90] Menna A. Saleh, Mohamed H. Al Haron, Aya A. Saleh, and Mahmoud Farag. **Fatigue behavior and life prediction of biodegradable composites of starch reinforced with date palm fibers**. *International Journal of Fatigue*, **103**:216–222, 2017. 24

[91] Ibrahem RA. **Effect of Date Palm Seeds on the Tribological Behaviour of Polyester Composites under Different Testing Conditions**. *Journal of Material Science Engineering*, **04**(06), 2015. 25

[92] Mahdi Alajmi and Abdullah Shalwan. **Correlation between mechanical properties with specific wear rate and the coefficient of friction of graphite/epoxy composites**. *Materials*, **8**(7):4162–4175, 2015. 25

[93] Ali S. Hammood. **Effect of erosion on water absorption and morphology for treated date palm fiber-reinforced polyester composites**. *International Journal of Mechanical and Mechatronics Engineering*, **15**(6):108–114, 2015. 25

[94] Anthony N Anyakora. **Investigation of Impact Strength Properties of Oil and Date Palm Frond Fiber Reinforced Polyester Composites**. (January 2013), 2013. 25

[95] Satchidananda Tripathy, Janaki Dehury, and Debasmita Mishra. **A Study on the effect of Surface treatment on the Physical and Mechanical properties of date-palm stem liber embedded epoxy composites**. *IOP Conference Series: Materials Science and Engineering*, **115**(1), 2016. 25

[96] Priyadarshi Tapas Ranjan Swain, Sankar Narayan Das, and Shakti Prakash Jena. **Manufacturing and study of thermo-mechanical behaviour of surface modified date palm leaf/glass fiber reinforced hybrid composite**. *Materials Today: Proceedings*, **5**(9):18332–18341, 2018. 25

[97] Hamid Kaddami, Alain Dufresne, Bertine Khelifi, Abdelkader Bendahou, Moha Taourirte, Mustapha Raihane, Nathalie Issartel, Henry Sautereau, Jean François Gérard, and Noureddine Sami. **Short palm tree fibers - Thermoset matrices composites**. *Composites Part A: Applied Science and Manufacturing*, **37**(9):1413–1422, 2006. 25

[98] Fernando Pacheco-Torgal and Said Jalali. **Cementitious building materials reinforced with vegetable fibres: A review**. *Construction and Building Materials*, **25**(2):575–581, 2011. 26

[99] Martina Ivaskova, Peter Kotes, and Miroslav Brodnan. **Air pollution as an important factor in construction materials deterioration in Slovak Republic**. *Procedia Engineering*, **108**:131–138, 2015. 26

[100] Vahid Afroughsabet and Togay Ozbakkaloglu. **Mechanical and durability properties of high-strength concrete containing steel and polypropylene fibers**. *Construction and Building Materials*, **94**:73–82, 2015. 26

[101] Pantea Rashiddadash, Ali Akbar Ramezanianpour, and Mahdi Mahdikhani. **Experimental investigation on flexural toughness of hybrid fiber reinforced concrete (HFRC) containing metakaolin and pumice**. *Construction and Building Materials*, **51**:313–320, 2014. 26

[102] O. Kayali, M. N. Haque, and B. Zhu. **Some characteristics of high strength fiber reinforced lightweight aggregate concrete**. *Cement and Concrete Composites*, **25**(2):207–213, 2003. 26

[103] Nesibe Gozde Ozerkan, Bappy Ahsan, Said Mansour, and Srinath R. Iyengar. **Mechanical performance and durability of treated palm fiber reinforced mortars**. *International Journal of Sustainable Built Environment*, **2**(2):131–142, 2013. 26, 27

[104] Katherine G. Kuder and Surendra P. Shah. **Processing of high-performance fiber-reinforced cement-based composites**. *Construction and Building Materials*, **24**(2):181–186, 2010. 26

[105] A. Lau and M. Anson. **Effect of high temperatures on high performance steel fibre reinforced concrete**. *Cement and Concrete Research*, **36**(9):1698–1707, 2006. 26

[106] Marco Di Prisco, Giovanni Plizzari, and Lucie Vandewalle. **Fibre reinforced concrete: New design perspectives**. *Materials and Structures/Materiaux et Constructions*, **42**(9):1261–1281, 2009. 26

[107] I. Merta and E. K. Tschegg. **Fracture energy of natural fibre reinforced concrete**. *Construction and Building Materials*, **40**:991–997, 2013. 26

[108] Xiangming Zhou, Seyed Hamidreza Ghaffar, Wei Dong, Olayinka Oladiran, and Mizi Fan. **Fracture and impact properties of short discrete jute fibre-reinforced cementitious composites**. *Materials and Design*, **49**:35–47, 2013. 26

[109] A. Kriker, G. Debicki, A. Bali, M. M. Khenfer, and M. Chabannet. **Mechanical properties of date palm fibres and concrete reinforced with date palm fibres in hot-dry climate**. *Cement and Concrete Composites*, **27**(5):554–564, 2005. 15, 26, 27

[110] Bekir Çomak, Alper Bideci, and Özlem Salli Bideci. **Effects of hemp fibers on characteristics of cement based mortar**. *Construction and Building Materials*, **169**:794–799, 2018. 26

[111] S. Abani, F. Hafsi, A. Kriker, and A. Bali. **Valorisation of Date Palm Fibres in Sahara Constructions**. *Energy Procedia*, **74**:289–293, 2015. 26, 27

[112] Mourad Chikhi, Boudjemaa Agoudjil, Abderrahim Boudenne, and Abdelkader Gherabli. **Experimental investigation of new biocomposite with low cost for thermal insulation**. *Energy and Buildings*, **66**:267–273, 2013. 27, 38, 54

[113] Mourad Chikhi. **Young's modulus and thermophysical performances of bio-sourced materials based on date palm fibers**. *Energy and Buildings*, **129**:589–597, 2016. 27, 38, 53

[114] Ines Amara, Atef Mazioud, Ines Boulaoued, and Abdallah Mhimid. **Experimental study on thermal properties of bio-composite (gypsum plaster reinforced with palm tree fibers) for building insulation**. *International Journal of Heat and Technology*, **35**(3):576–584, 2017. 27, 31

[115] Aymen Braiek, Mustapha Karkri, Ali Adili, Laurent Ibos, and Sassi Ben Nasrallah. **Estimation of the thermophysical properties of date palm fibers/gypsum composite for use as insulating materials in building**. *Energy and Buildings*, **140**:268–279, 2017. 27, 31, 38, 44, 52

[116] Bourhaneddine Haba, Boudjemaa Agoudjil, Abderrahim Boudenne, and Karim Benzarti. **Hygric properties and thermal conductivity of a new insulation material for building based on date palm concrete**. *Construction and Building Materials*, **154**:963–971, 2017. 27

[117] Oussama Benaimeche, Andrea Carpinteri, Mekki Mellas, Camilla Ronchei, Daniela Scorza, and Sabrina Vantadori. **The influence of date palm mesh fi bre reinforcement on flexural and fracture behaviour of a cement-based mortar**. *Composites Part B*, **152**(March):292–299, 2018. 27, 48, 57

[118] Mokhtar Rachedi and Abdelouahed Kriker. **Thermal properties of plaster reinforced with date palm fibers**. *Civil and Environmental Engineering*, **16**(2):259–266, 2020. 27, 38

[119] Samir Benaniba, Zied Driss, Mokhtar Djendel, Elhadj Raouache, and Rabah Boubaaya. **Thermo-mechanical characterization of a bio-composite mortar reinforced with date palm fiber**. *Journal of Engineered Fibers and Fabrics*, **15**, 2020. 27, 44, 54, 57

[120] Nadia Benmansour, Boudjemaa Agoudjil, Abdelkader Gherabli, and Abdelhak Kareche. **Thermal and mechanical performance of natural mortar reinforced with date palm fibers for use as insulating materials in building**. *Energy Buildings*, **81**:98–104, 2014. 27

[121] Musa Adamu, Yasser E. Ibrahim, Oussama Elalaoui, Hani Alanazi, and Nageh M. Ali. **Modeling and Optimization of Date Palm Fiber Reinforced Concrete Modified with Powdered Activated Carbon under Elevated Temperature**. *Sustainability (Switzerland)*, **15**(8), 2023. 27

[122] A. Elena Charola, Josef Pühringer, and Michael Steiger. **Gypsum: A review of its role in the deterioration of building materials**. *Environmental Geology*, **52**(2):207–220, 2007. 31

[123] Xiaoliang Ding, Yi Li, Wen Huang, Lu Chen, Yanzhi You, Hua Chen, and Zhijun Hu. **Green and effective route to convert chromium-free**

**leather waste into protein retarding material for building gypsum**. *Construction and Building Materials*, **411**(December 2023), 2024. 31

[124] ASTM International. **ASTM C642-13: Standard Test Method for Density, Absorption, and Voids in Hardened Concrete**. West Conshohocken, PA, 2013. 34, 39, 40

[125] ASTM International. **ASTM D4404-18 - Standard Test Method for Determination of Pore Volume and Pore Volume Distribution of Soil and Rock by Mercury Intrusion Porosimetry**. ASTM D4404-18, 2018. 34

[126] ASTM E982-10. **ASTM E982-10(2015), Standard Guide for Analysis and Interpretation of SEM Images**. ASTM International, 2015. 35

[127] ASTM E1777-96. **ASTM E1777-96 (2018), Standard Guide for X-ray Powder Diffraction**. ASTM International, 2018. 36

[128] ASTM E1252-98. **ASTM E1252-98(2018), Standard Practice for General Techniques for Obtaining Infrared Spectra for Qualitative Analysis**. ASTM International, 2018. 37

[129] ASTM E1131-20. **ASTM E1131-20, Standard Test Method for Compositional Analysis by Thermogravimetry**. ASTM International, 2020. 37

[130] NF P18-560. **NF P18-560: Aggregates - Particle Size Distribution by Sieving**, 1990. 38

[131] ASTM C28/C28M-10. **ASTM C28/C28M-10(2015), Standard Specification for Gypsum Plasters**. ASTM International, 2015. 38

[132] ASTM International. **ASTM C109 / C109M-20, Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens)**. West Conshohocken, PA, 2020. 41

[133] ASTM International. **ASTM C518-21, Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus**. `www.astm.org`, 2021. 41

[134] Mohammad Asim, Mohammad Jawaid, Anish Khan, Abdullah M. Asiri, and Maqsood Ahmad Malik. **Effects of Date Palm fibres loading on mechanical, and thermal properties of Date Palm reinforced phenolic composites**. *Journal of Materials Research and Technology*, **9**(3):3614–3621, 2020. 44

[135] Mohamed E. Ali and Abdullah Alabdulkarem. **On thermal characteristics and microstructure of a new insulation material extracted from date palm trees surface fibers**. *Construction and Building Materials*, **138**:276–284, 2017. 44

[136] Hani H. Sait, Ahmad Hussain, Arshad Adam Salema, and Farid Nasir Ani. **Pyrolysis and combustion kinetics of date palm biomass using thermogravimetric analysis**. *Bioresource Technology*, **118**:382–389, 2012. 48

[137] Chouaib Fethiza Tedjani, Omar Ben Mya, and Abdelkrim Rebiai. **Isolation and characterization of cellulose from date palm tree spathe sheath**. *Sustainable Chemistry and Pharmacy*, **17**(July):100307, sep 2020. 48

[138] Abdullah Alabdulkarem, Mohamed Ali, Gino Iannace, Shereef Sadek, and Redhwan Almuzaiqer. **Thermal analysis, microstructure and acoustic characteristics of some hybrid natural insulating materials**. *Construction and Building Materials*, **187**:185–196, 2018. 50

[139] M. R. Sanjay, P. Madhu, Mohammad Jawaid, P. Senthamaraikannan, S. Senthil, and S. Pradeep. *Characterization and properties of natural fiber polymer composites: A comprehensive review*, **172**. Elsevier B.V., 2018. 50

[140] Rungsima Chollakup, Wirasak Smitthipong, Wuttinan Kongtud, and Rattana Tantatherdtam. **Polyethylene green composites reinforced with cellulose fibers (coir and palm fibers): Effect of fiber surface treatment and fiber content**. *Journal of Adhesion Science and Technology*, **27**(12):1290–1300, 2013. 50

[141] M. Chandrasekar, K. Senthilkumar, M. Jawaid, Salman Alamery, Hassan Fouad, and Mohamad Midani. **Tensile, Thermal and Physical Properties of Washightonia Trunk Fibres/Pineapple Fibre Biophenolic Hybrid Composites**. *Journal of Polymers and the Environment*, **30**(10):4427–4434, 2022. 50, 51

[142] Mohammad Jawaid, Lau Kia Kian, H Fouad, N Saba, Othman Y Alothman, and Mohamed Hashem. **New Cellulosic Fibers from Washingtonia Tree Agro-wastes: Structural, Morphological, and Thermal Properties**. *Journal of Natural Fibers*, **19**(13):5333–5343, 2022. 50

[143] Amina Hachaichi, Benalia Kouini, Lau Kia Kian, Mohammad Asim, Hassan Fouad, Mohammad Jawaid, and Mohini Sain. **Nanocrystalline Cellulose from Microcrystalline Cellulose of Date Palm Fibers as a Promising Candidate for**. *Materials*, pages 1–12, 2021. 50

[144] Amina Hachaichi, Benalia Kouini, Lau Kia Kian, Mohammad Asim, and Mohammad Jawaid. **Extraction and Characterization of Microcrystalline Cellulose from Date Palm Fibers using Successive Chemical Treatments**. *Journal of Polymers and the Environment*, **29**(6):1990–1999, 2021. 50

[145] Francesco Barreca and Pasquale Praticò. **Assessment of passive retrofitting strategies to improve the thermal performance of extra-virgin olive oil storage area in traditional rural olive mills**. *Sustainability (Switzerland)*, **12**(1), 2020. 52

[146] Manuel Álvarez, Daniel Ferrández, Carlos Morón, and Evangelina AtanesâĂŘSánchez. **Characterization of a new lightened gypsumâĂŘbased material reinforced with fibers**. *Materials*, **14**(5):1–19, 2021. 52

[147] Drifa Belkharchouche and Abla Chaker. **Effects of moisture on thermal conductivity of the lightened construction material**. *International Journal of Hydrogen Energy*, **41**(17):7119–7125, 2016. 52

[148] E. Aamr-Daya, T. Langlet, A. Benazzouk, and M. Quéneudec. **Feasibility study of lightweight cement composite containing flax by-product particles: Physico-mechanical properties**. *Cement and Concrete Composites*, **30**(10):957–963, 2008. 52

[149] A. Hakamy, Fua Shaikh, and I. M. Low. **Microstructures and mechanical properties of hemp fabric reinforced organoclay-cement nanocomposites**. *Construction and Building Materials*, **49**:298–307, 2013. 52

[150] Abu Yaya, Joseph Daafuor, Elsie Bowen-dodoo, and E Nyankson. **Mechanical and statistical analysis of polypropylene composites derived from mixed clay-oil palm fruit particles MECHANICAL AND STATISTICAL ANALYSIS OF POLYPROPYLENE COMPOSITES DERIVED FROM MIXED CLAY-OIL PALM FRUIT PARTICLES**. (December), 2018. 53

[151] N Sakthieswaran and M Sophia. **Environmental Technology Innovation Prosopis juliflora fibre reinforced green building plaster materials âĂŤ An**

**eco-friendly weed control technique by effective utilization**. *Environmental Technology Innovation*, **20**:101158, 2020. 53

[152] Thorsak Kittikorn, Emma Strömberg, Monica Ek, and Sigbritt Karlsson. **Comparison of water uptake as function of surface modification of empty fruit bunch oil palm fibres in PP biocomposites**. *BioResources*, **8**(2):2998–3016, 2013. 53

[153] Jie Liu and Chun Lv. **Research Progress on Durability of Cellulose Fiber-Reinforced Cement-Based Composites**. *International Journal of Polymer Science*, **2021**, 2021. 53

[154] Nadezda Stevulova, Vojtech Vaclavik, Viola Hospodarova, and Tomáš Dvorský. **Recycled cellulose fiber reinforced plaster**. *Materials*, **14**(11):1–26, 2021. 53

[155] S Sair, B Mandili, M Taqi, and A Elbouari. **Development of a new eco-friendly composite material based on gypsum reinforced with a mixture of cork fibre and cardboard waste for building thermal insulation**. *Composites Communications*, 2019. 53, 57

[156] Joseph Khedari, Borisut Suttisonk, Naris Pratinthong, and Jongjit Hirunlabh. **New lightweight composite construction materials with low thermal conductivity**. *Cement and Concrete Composites*, **23**(1):65–70, 2001. 53, 58

[157] Mohammed Mohammed, M. S.M. Rasidi, Aeshah M. Mohammed, Rozyanty Rahman, Azlin F. Osman, Tijjani Adam, Bashir O. Betar, and Omar S. Dahham. **Interfacial Bonding Mechanisms of Natural Fibre-Matrix Composites: An Overview**. *BioResources*, **17**(4):7031–7090, 2022. 54

[158] Sebastien Migneault, Ahmed Koubaa, Fouad Erchiqui, Abdelkader Chaala, Karl Englund, and Michael P. Wolcott. **Effects of processing method and fiber size on the structure and properties of wood-plastic composites**. *Composites Part A: Applied Science and Manufacturing*, **40**(1):80–85, 2009. 54

[159] José Guillermo Torres-Rendón, Mario E. Valdez-Fausto, José Anzaldo-Hernández, Rosa M. Jiménez-Amezcua, Kestur G. Satyanarayana, Salvador García-Enriquez, and María Guadalupe Lomelí-Ramírez. **Preparation and characterization of nanocomposites based**

**on linear medium density polyethylene/cellulose nanofibers from Agave tequilana Bagasse Waste**. *BioResources*, **14**(4):9806–9825, 2019. 54

[160] Said Bouzit, Said Laasri, Mohamed Taha, Abdelaziz Laghzizil, Abdelowahed Hajjaji, Francesca Merli, and Cinzia Buratti. **Characterization of natural gypsum materials and their composites for building applications**. *Applied Sciences (Switzerland)*, **9**(12), 2019. 58

[161] Younouss. Dieye, Pape M. Toure, Seckou. Bodian, Prince M. Gueye, Mactar. Faye, and Vincent. Sabourin. **Study of thermal and mechanical properties of typha leaf - clay panels**. *Journal of Sustainable Construction Materials and Technologies*, **6**(December):135–142, 2021. 58

[162] Mohamed Sawadogo, Marie Duquesne, Rafik Belarbi, Ameur El Amine Hamami, and Alexandre Godin. **Review on the integration of phase change materials in building envelopes for passive latent heat storage**. *Applied Sciences (Switzerland)*, **11**(19), 2021. 58

[163] Noor Fifinatasha Shahedan, Mohd Mustafa Al Bakri Abdullah, Norsuria Mahmed, Andri Kusbiantoro, Sam Tammas-Williams, Long Yuan Li, Ikmal Hakem Aziz, PetricĂČ Vizureanu, Jerzy J. Wysłocki, Katarzyna Błoch, and Marcin Nabiałek. **Properties of a new insulation material glass bubble in geo-polymer concrete**. *Materials*, **14**(4):1–17, 2021. 58