UNIVERSITI PUTRA MALAYSIA

ENHANCEMENT OF EVALUATION METHODOLOGIES FOR NATURAL FIBER COMPOSITES MATERIAL SELECTION SYSTEM

FARIS MOHAMMED KHAIR FARIS AL-OQLA

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By

FARIS MOHAMMED KHAIR FARIS AL-OQLA

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

March 2015

DEDICATION

This thesis is gratefully dedicated to:

My Beloved Mother for her unlimited sacrifices, encouragements and support throughout my life

The soul of my Father

My Wife for her patience and understanding

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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March 2015

Chairman: Mohd Sapuan Salit, PhD, PEng

Faculty: Engineering

Proper evaluations of natural fiber composites (NFCs) and their constituents are of paramount importance in making informative decisions toward enhancing their selection process for future sustainable design possibilities. Consequently, this study was conducted to develop evaluation methodologies and selection models to properly evaluate and develop the selection system of the NFCs and their constituents as well as to discover new potential natural fiber types capable for improving the NFCs' desirable characteristics. Hence, this study started with identifying the gap in evaluating the available natural fiber types relative to comprehensive desired criteria, then building a categorization framework to categorize and classify criteria that affect NFCs and their products into appropriate levels. Five distinguished levels were introduced as a primary evaluation tool for designers in this field. Moreover, the feasibility of using the date palm fiber (DPF) type in NFCs for automotive industry was investigated utilizing selected criteria from the presented levels. In contrast, a combined multi-criteria evaluation stage technique (CMCEST) was also introduced as a new systematic, simple and efficient indicator to enhance better evaluations of the available natural agro wastes for polymeric-based composites. In the proposed technique, sequence of evaluation stages where introduced as: single-evaluation-criterion (SEC), combined-double-evaluation-criterion (CDEC), combined-triple-evaluation-criterion (CTEC), etc. The CMCEST enhancements can reveal new potential fiber types through better evaluation schemes. Furthermore, this work developed and introduced a novel systematic evaluation methodology for natural fibers' capabilities based on moisture content criterion (MCC). This MCC evaluation tool was designed to predict the behavior of the available natural fibers regarding distinctive desirable characteristics under the effect of the moisture absorption phenomenon. MCC is capable of enhancing the selection process of NFCs for better sustainable design possibilities. In addition, efforts were integrated to enhance and develop the selection process of NFCs' constituents to achieve a real novel progress in this field. Thus, a decision making model was developed to rank and evaluate various available polymers to determine the most appropriate polymer matrix type for natural fiber composites considering twenty different criteria standpoints simultaneously. Moreover, this study also developed decision-support models to evaluate and select the optimal reinforcement conditions of the Date Palm/Epoxy composite to maximize its overall tensile property considering

combined evaluation criteria. The usefulness of the developed evaluation methodologies and models was successfully demonstrated through their capabilities in enhancing better evaluations of the NFCs regarding wide range of multiple conflicting criteria as well as eliminating the bias or prejudice in decisions and reduce human errors in the selection process.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENINGKATAN BAGI PERKAEDAHAN PENILAIAN UNTUK SISTEM PEMILIHAN BAHAN KOMPOSIT GENTIAN SEMULA JADI

Oleh

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Penilaian yang betul bagi komposit gentian semula jadi (NFCs) dan kandungan mereka adalah amat penting dalam membuat keputusan bermaklumat ke arah meningkatkan proses pemilihan mereka untuk kemungkinan reka bentuk masa depan yang mampan. Oleh yang demikian, kajian ini dijalankan untuk membangunkan perkakas penilaian dan model pemilihan untuk menilai dengan betul dan membangunkan proses pemilihan bagi NFCs dan kandungan mereka serta untuk mengenali potensi jenis gentian semula jadi baharu yang mampu untuk meningkatkan ciri-ciri yang diingini bagi NFCs. Oleh itu, kajian ini bermula dengan mengenal pasti jurang dalam menilai jenis gentian semula jadi yang ada berbanding dengan kriteria yang dikehendaki komprehensif, kemudian, satu pengkategorian rangka kerja telah disampaikan untuk mengkategorikan dan mengelaskan kriteria yang mempengaruhi NFCs dan produk mereka ke tahap yang sesuai. Lima tahap yang jelas telah diperkenalkan sebagai perkakas penilaian utama bagi pereka dalam bidang NFCs. Selain itu, kemungkinan menggunakan jenis gentian pokok kurma (DPF) dalam NFCs untuk industri automotif telah dikaji menggunakan kriteria yang dipilih daripada peringkat dibentangkan. Sebaliknya, kaedah peringkat penilaian multi-kriteria gabungan (CMCEST) juga diperkenalkan sebagai petunjuk baharu yang sistematik, mudah dan berkesan untuk meningkatkan penilaian yang lebih baik daripada sisa pertanian semula jadi yang wujud untuk komposit berasaskan polimer. Dalam kaedah yang dicadangkan, urutan peringkat penilaian di mana diperkenalkan sebagai: kriteria penilaian sendiri (SEC), kriteria penilaian digabungkan-dua (CDEC), kriteria penilaian digabungkan-triple (CTEC), dan lain-lain. Penambahan CMCEST boleh mendedahkan jenis gentian potensi baharu melalui skim penilaian yang lebih baik. Tambahan pula, kerja ini membangunkan dan memperkenalkan satu perkakas penilaian yang sistematik yang baharu bagi keupayaan gentian semula jadi berdasarkan kriteria kandungan kelembapan (MCC). Alat penilaian MCC ini telah direka untuk meramalkan kelakuan gentian semula jadi yang ada berkaitan ciri-ciri tersendiri yang dikehendaki di bawah kesan fenomena penyerapan kelembapan. MCC mampu menilai gentian semula jadi dengan lebih baik dengan cara yang sistematik, dan oleh itu meningkatkan proses pemilihan untuk kemungkinan reka bentuk yang lebih baik mampan. Di samping itu, usaha dipersepadu untuk meningkatkan dan

membangunkan proses pemilihan kandungan NFCs untuk mencapai kemajuan baharu yang sebenar dalam bidang ini. Oleh itu, satu model membuat keputusan telah dibangunkan untuk menentukan kedudukan dan menilai pelbagai polimer yang ada untuk menentukan jenis matriks polimer yang paling sesuai untuk komposit gentian semula jadi. Ini dilakukan dengan menentukan merit relatif mereka mengenai dua puluh kriteria yang berbeza pada masa yang sama. Selain daripada itu, kajian ini juga membangunkan satu model sokongan keputusan untuk menilai dan memilih keadaan tetulang optimum bagi komposit pokok kurma/epoksi untuk memaksimumkan sifat tegangan keseluruhannya dengan mempertimbangkan kriteria penilaian yang digabungkan. Kebergunaan perkakas dan model penilaian yang dibangunkan telah berjaya mempamerkan melalui keupayaan mereka dalam meningkatkan penilaian yang lebih baik daripada kandungan NFCs mengenai pelbagai kriteria yang berbilang serta menghapuskan berat sebelah atau prejudis dalam membuat keputusan dan mengurangkan kesilapan manusia dalam proses pemilihan.

ACKNOWLEDGEMENTS

First, my praise to Almighty Allah for giving me the power and will to complete this work.

I particularly would like to express my appreciation and profound gratitude to the chairman of supervisory committee, Professor Mohd Sapuan Salit for his invaluable advice, guidance, effort, and supervision. You always believed in me, and showed a positive attitude throughout my study. I also would like to convey my thanks to the members of supervisory committee, Associate Professor Nuraini Abdul Aziz and Dr. Mohamad Ridzwan Ishak, for sharing their expertise and for continuous guidance and suggestions that enriched the study.

I have no enough words to express my profuse thanks to my family for their unconditional love and endless support that gave me the strength to complete this work, especially the unlimited sacrifices of my Mother. Special thanks are extended to my wife, for her understanding, patience and efforts. It is worth to mention all my friends for their support and cooperation.

I'm very grateful to the anonymous referees for their respectful valuable comments on the manuscripts of journal papers. Thanks to my colleagues and staff in the Faculty of Engineering (UPM) for their advice, assistance and kindness.

School of Graduate Studies at Universiti Putra Malaysia is acknowledged for supporting my PhD study through an international graduate research fellowship (IGRF) scheme.

I certify that a Thesis Examination Committee has met on 23 March 2015 to conduct the final examination of Faris Mohammed Khair Faris AL-Oqla on his thesis entitled "Enhancement Of Evaluation Methodologies For Natural Fiber Composites Material Selection System" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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I hereby confirm that:

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AHP	Analytical Hierarchy Process
AIP	Acoustic Insulation Properties
C	Cost
CC	Composite Characteristics
CDEC	Combined-Double-Evaluation-Criterion
CI	Consistency Index
CM	Curing Time
CMCEST	Combined Multi-Criteria Evaluation Stage Technique
CP	Composite Performance
CR	Consistency Ratio
CT	Curing Temperature
CTE	Coefficient of Thermal Expansion
CTEC	Combined-Triple-Evaluation-Criterion
CTPPM	Chemical / Technical Properties of the Polymer Matrix
D	Density
DM	Decision Making
DPF	Date Palm Fiber
EB	Elongation to Break
EM	Elastic Modulus
EOPPM	Environmental and Other Properties of the Polymer Matrix
FD	Fiber Diameter
FL	Fiber Length
FT	Fracture Toughness
GTT	Glass Transition Temperature
HDPE	High Density Polyethylene
IS	Impact Strength
LDPE	Low Density Polyethylene
LHN	Level of Hydrophobic Nature
MC	Moisture Content
MCC	Moisture Content Criterion
MCDM	Multi Criteria Decision Making
MPPM	Mechanical Properties of the Polymer Matrix
MSS	Maximum Shear Stress
MTS	Maximum Tensile Strength
NaOH	Sodium Hydroxide
NFCs	Natural Fiber Composites
NFP	Natural Fiber Properties
NFRPC	Natural Fiber Reinforced Polymer Composites
NOR	Normalized
PBP	Polymer Base Properties
PP	Polypropylene
PPPM	Physical Properties of the Polymer Matrix
RC	Resistance of Chemicals
RI	Random Index

SAW	Simple Additive Weighted
SEC	Single-Evaluation-Criterion
SEM	Scanning Electron Microscope
SR	Sunlight and UV Resistance
ST	Service Temperature
TC	Thermal Conductivity
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
VIKOR	Vise Kriterijumska Optimizacija Kompromisno Resenje
W	Wettability
WPM	Weighted Product Method
WR	Weather Resistance
YS	Yield Strength

CHAPTER 1

INTRODUCTION

1.1 Background

Natural fibers have been utilized as reinforcements to produce composite materials since long time ago. It was reported that both linen and hemp were used to reinforce ceramics as early as 6500 BC [1]. Since that time, natural fiber composites (NFCs) have been implemented in different applications for human beings. While E-glass and other synthetic fibers dominate today's fiber reinforced polymer market, several factors have led to a renewed interest in such type of bio-based composites. Such factors include awareness of the scarcity of non-renewable natural resources, high petroleum prices, demands for environmental sustainability, and reducing the amount of environmental pollutions. The increasing number of publications on bio-based composites during the recent years [2, 3], is an obvious indication for the ever-increasing interest in such composites.

More precisely, natural fiber composites have recently emphasized to be potential eco-friendly cheap alternatives for the traditional composites due to their desired features. This type of materials, where plant fibers like coir, hemp, jute, sisal etc. are used as reinforcements for polymer matrices, possesses several distinguished characteristics including low costs, light weights, high specific properties, ease of manufacturing, recyclability as well as degradability features [4, 5]. Such advantages of NFCs, in addition to the tremendous needs toward achieving better environmental performance indices [6] as well as enhancing the sustainable development in modern societies [7] have revealed the eligibility of natural fibers and their composites for various industrial applications. It was reported that over 95% of the commercially produced NFCs in EU were mainly utilized in non-structural automotive components, particularly, the interior ones such as doors and instrumental panels [1, 8]. However, NFCs are being considered in other various applications [1, 8-10] like: furniture and consumer goods (such as packaging, cases, helmets, tables, chairs, ironing boards and urns), construction and infrastructure (such as beams, roof panels and bridges), sports and leisure (such as bicycle frames, tennis rockets and canoes), in addition to others like wind energy, aerospace, marine, bio-engineering and environmental applications [3, 11, 12]. In all such applications, plant fibers are usually used as reinforcements and fillers rather than the traditional synthetic ones due to their advantages over the later. The available natural fibers include, rice husk, cotton, pineapple leaf, bagasse, flax, wood, hemp, coir, oil palm, date palm kenaf, sisal, jute as well as others. The advantages of such natural fibers include their good thermal and acoustical insulation properties, low cost, light weight, biodegradability characteristics, wide availability, eco-friendly, energy recovery, reduced tool wear in machining operations, CO2 sequestration enhanced, and reduced dermal and respiratory irritation [3, 5, 10, 13]. In fact, different industrial applications have used various natural fiber types according to certain limited criteria such as availability, density, and cost, in addition to some mechanical properties like fiber's tensile strength, fiber's tensile modulus and elongation to break criteria. Hence, there are still wide different natural fiber types that are not properly valorized or commercially utilized.

1.2 Significance of Study

Based on the fact that the available natural fibers have different capabilities and properties from various chemical, physical, and mechanical standpoints, and because the final features of NFCs strongly depend on the integrated characteristics of their constituents (fillers and matrices), several factors and constrains may affect the proper selection of the NFCs' constituents to form desirable composites for a particular application. This in order makes the selection of NFCs and their constituents is a matter of multi criteria decision making (MCDM) problem where appropriate keen decisions have to be taken not only to maximize the composites desirable characteristics, but also to save both money and efforts. Consequently, developing evaluation tools and models to proper evaluate the capabilities of the available natural fibers in one hand, and to develop the selection system of the natural fiber composites and their constituents on the other, are of paramount importance to be conducted. This in order, would not only enhance establishing the selection system in the field of natural fiber composites, but also expand the sustainable design possibilities for future green products. Moreover, better evaluations and selections of the natural fibers, with emphasis on a particular type, through proper evaluation tools and models, would lead not only to discover new potential natural fiber types to improve the composite's desirable characteristics, but also to help finding proper environmental waste management practices.

1.3 Problem Statements

Considering the tremendous need and awareness of the environmental impact issues and the industrial sustainability, the compatibility between the available natural resources and the sustainable industry has been recently highly emphasized. One of the most feasible alternatives for the industry to maintain its sustainability in one hand, and to achieve better environmental performance on the other, is the implementation of the natural fiber composites (NFCs) in their designs and products [2, 6, 11]. However, the variety in agro waste sources dramatically affects their qualities and capabilities from different standpoints, which lead to affect the final performance of their natural fiber composites. Such varieties in natural fibers make a particular fiber type is more suitable for a certain polymer matrix as well as an application rather than others.

Moreover, there was an extreme shortage in methodologies and tools for evaluating different constituents of NFCs, where only little studies were found considering the selection of natural fiber composites for industrial applications. This is basically due to the conflicting criteria involved in the selection process that make it a complex matter. Therefore, an improper way in evaluating natural fiber composites and their constituents relative to comprehensive desired criteria was indicated, which leads to disregard potential natural fiber types in industrial applications and keeps them no more than an environmental waste problem issue. On consequence, such improper evaluations reduce the possibilities of maximizing the desirable characteristics of NFCs for a particular application and lead to destroy the proper linkage between the sustainable design concepts and the industry. This also negatively affects the implementation of NFCs in various applications. Therefore, efforts for developing evaluation tools and methodologies to enhance the selection of NFCs and their constituents are of tremendous need.

Furthermore, only limited numbers of the available natural fiber types are commercially utilized in industrial applications while other plenty types, such as the date palm fiber (DPF), are not properly valorized. This is due to the facts that: 1) proper evaluations of natural fibers for industrial applications have not been adequately discussed regarding wide range of desired criteria, and 2) the selection of the natural fiber types for making NFCs is still depending on the researchers' estimations or limited evaluation standpoints. Thus, a lack of information regarding selecting the proper natural fiber type for NFCs was also indicated. On the other hand, to optimize the performance of natural fiber composites, both physio-chemical and mechanical behavior knowledge for their constituents (natural fibers and polymers) are required. This is due to the fact that the final properties of NFCs depend on the matrix type, fiber type, and their interfacial bonding, where the compatibility and reinforcement efficiency between the composite's constituents are necessary. However, based on the literature, there were: a) No clear systematic and comprehensive classification of the factors and criteria that affect the selection process of the natural fiber composites and their constituents. b) Lack of information regarding proper evaluations of the natural fibers' capabilities considering wide and/ or combined beneficial criteria. c) Lack of information regarding precise decisions for selecting NFCs and their constituents for applications with conflicting criteria. d) Lack of information regarding ranking and predicting the potential and behavior of various natural fiber types under wet conditions to enhance their selection process for particular applications. e) Lack of information regarding evaluating the available polymer types for a particular natural fiber and application considering wide evaluation criteria simultaneously. f) Lack of information for selecting the most appropriate reinforcement conditions of a particular composite to maximize its overall performance regarding a set of beneficial evaluation criteria simultaneously.

In addition, it was noticed that despite of the growing need for implementing decision-making models as well as other beneficial tools to enhance achieving more sustainable societies [7]. There were no systematic decision making models that can utilize experts' knowledge in the field of natural fiber composites to predict the appropriateness of NFCs and their constituents regarding conflicting evaluation criteria to maximize the desired characteristics and performance.

On the other hand, despite of the availability of several computer database packages and commercial material selection software types like Cambridge Engineering Selector (CES), commercial Computer Aided Design (CAD) environment, expert systems, knowledge based systems (KBS) and Application Programming Interface (API) modules that facilitate demonstrating different material properties for the designers [14, 15], no distinguished evaluation methodologies are existed in such packages neither for traditional materials nor natural fiber composite ones [16-19]. They have only management systems which recover and manipulate the data, and graphical user interface that present the property data as material selection charts. For instance, in order to select a material with such CES software, a series of selection stages have to be performed. At each stage, either a user-defined functions of material properties (like ultimate tensile strength per density) or a pair of material properties have to be specified as the axes for generating graphs with these properties, and thus, all materials contained in the database with applicable data entries are plotted on the graph [20]. Then the materials which lie in the area that satisfies the selection criterion are considered to have ‘passed’ the selection stage. After that, several stages should be performed to quickly narrow the field of possible potential materials to a manageable few. This in order makes such software types no more than fast material screening tools [21]. However, due to the large conflicting criteria involved in the material selection, proper evaluations of the available materials and their constituents (particularly for NFCs) are of paramount importance to be performed to properly rank the material choices for identifying the optimal one(s) [18]. However, this not practically occurs in such available commercial software. Moreover, any type of material screening regarding various evaluations through “stages passing” scheme would lead to ignoring potential types of materials with better performance than a reference one. More and above that, non-concurrent combined material property evaluations will decelerate the convergence in material screening. Therefore, there are practical limitations in the available material selection systems regarding evaluating and ranking the available material types for conflicting desirable characteristics. Thus, new proper evaluation methodologies are still needed particularly for the natural fiber composites to develop and enhance their proper selection system for various industrial applications.

Consequently, the intention of this work is to develop evaluation tools and models to properly evaluate the capabilities of the available natural fiber types in one hand, and to develop the selection process of the natural fiber composites and their constituents to improve their desirable characteristics for further industrial implementations on the other. Moreover, its purpose is also extended to participate discovering the potential of the date palm fiber type for natural fiber composites compared to commonly used ones through the developed evaluation tools. This is to serve as a tool to support benchmarking toward establishing for better evaluation of the available natural fibers and discovering the potential of other new fiber types in order to expand the sustainable design possibilities and help finding proper environmental waste management practices.

1.4 Objectives

The objectives of this research work are to:

1. Build a categorization framework for the criteria and factors that affect natural fiber composites and their products.
2. Develop new evaluation tools for better evaluation of the available natural fibers’ capabilities to enhance their selection process for polymeric based composites.
3. Build decision making selection models to enhance better evaluations and selections of the natural fiber composites and their constituents considering simultaneous multiple evaluation criteria.
4. Utilize the developed evaluation tools and models to discover the potential of the date palm fibers for natural fiber composites.

1.5 Scope and Limitations

Although there are many sources of natural fibers, this research is limited to study the potential of using plant fibers in the natural fiber composites. The considered fibers are limited to some of those commonly used in industrial applications in addition to the date palm fiber, namely; coir, flax, jute, hemp, kenaf, oil palm and sisal. On the other hand, due to the undesirable technical drawback of natural fibers such as the low permissible processing temperature, the considered polymer alternatives in this study were some of those that were found suitable for the date palm fibers to avoid the possibility of any lignocellulosic degradation and to prevent volatile emissions that could hurt composite characteristics and were limited to polypropylene, polyester, epoxy, high density polyethylene, and low density polyethylene. For each considered fiber and polymer type limited numbers of properties were utilized in the study. The considered properties of fibers were limited in this study to: density, length, diameter, length to diameter ratio, thermal conductivity, cellulose, hemicellulose and lignin contents, moisture content, availability, raw fiber cost per weight, tensile strength, tensile modulus, elongation to break, specific tensile modulus, specific tensile strength, specific elongation to break, maximum shear stress, cost ratio, specific modulus of elasticity to cost ratio, specific tensile strength to cost ratio, specific elongation to cost ratio, and the governmental support and social positive view. On the other hand, the properties of polymers were limited to: density, thermal conductivity, coefficient of thermal expansion, glass transition temperature, acoustic insulation properties, elastic modulus, fracture toughness, elongation to break, yield strength, impact strength, curing temperature, curing pressure, curing time, resistance of chemicals, level of hydrophobic nature, weather resistance, service temperature, sunlight and UV resistance, wettability, and the polymer cost. For comparison purposes, the assigned values for all of the considered properties and criteria were either utilized as the average of the reported values in peer reviewed journals, or their relative merits were surveyed as worldwide experts' feedback. In addition, some ratios were calculated based on the average reported values of the considered properties. For fibers that have more than one origin, the average value of the different origins was considered regarding a particular property. In developing the decision making models, only the Analytical Hierarchy Process (AHP) as a decision making tool was utilized. However, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method was also implemented in the case of selecting the best reinforcement conditions of DPF/ Epoxy composites for general applications to increase the validity of the gained results.

1.6 Thesis Outline

The thesis consists of nine chapters. This chapter; Chapter 1, gives a general introduction to the considered subjects in addition to the significance of the work, problem statement, objectives, scope and limitations and the thesis outline itself. Chapter 2 provides a general literature survey about natural fiber composites and their constituents with useful physical, mechanical, chemical as well as other properties of natural fibers. It also provides a general literature about material selection using multi-criteria decision making methods as well as the ways of selecting natural fiber composites. Besides, the methodologies by which the current work was approached are expressed in details in Chapter 3. Moreover, the central parts of the current work are illustrated in other five chapters, Chapter 4 to Chapter 8, where each chapter contains an added value step research toward accomplishing the objectives of the current thesis. That is; Chapter 4 presents a categorization frame work for the criteria and factors that affect natural fiber composites and their products. It also addresses the gap in evaluating natural fibers as well as investigates the feasibility of the date palm fiber type for the automotive industry compared with commonly used fibers. Chapter 5 introduces a combined multi-criteria evaluation scheme to enhance better evaluations of the available agro waste fibers to reduce the gap addressed in the previous chapter. In addition, Chapter 6 comes to support the selection process of the natural fibers for the natural fiber composites under wet conditions by presenting a novel evaluation tool for predicting and evaluating the natural fibers' performance under the effect of water absorption phenomenon based on the moisture content criterion. Furthermore, to integrate efforts in the current work toward achieving a real novel progress in the field of natural fiber composites' selection, Chapter 7 introduces a decision making selection model for evaluating different polymer types considering twenty various evaluation criteria simultaneously, in order to determine and select the most appropriate matrix type for the natural fiber composites. In this chapter a model for selecting the most appropriate matrix type for the date palm fiber was built and discussed in details to serve as a benchmarking tool and a guide for polymer selections in the field of natural fiber composites. Chapter 8 completes the current work's objectives as well as the desired aspects of enhancing the natural fiber composites selection system. More precisely, it presents another benchmarking model with an integrated decision scheme for evaluating a particular composite type and selecting the optimal reinforcement conditions that can maximize its desired characteristics with respect to a combination of various conflicting criteria simultaneously. Finally, general conclusions and recommendations for future research were allocated in Chapter 9.

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