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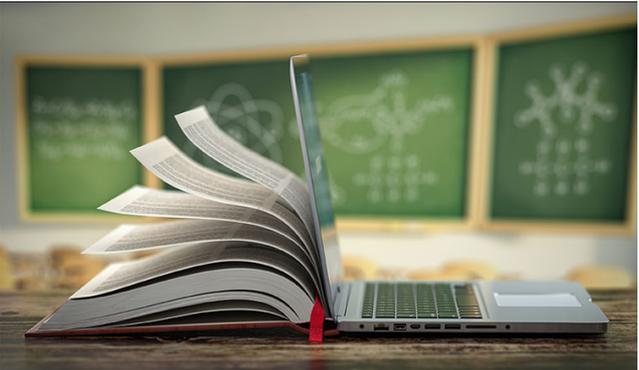
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Multivariable analysis for selection of natural fibers as fillers for a sustainable food packaging industry

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Keywords: food packaging, natural fibres, multivariable analysis, analytic hierarchy process, TOPSIS

Abstract

There is a rising demand for advanced new materials in food packaging to meet the growing economic and sustainability requirements. Natural fibers have excellent mechanical and thermal isolation properties and lower production costs than synthetic fibers, making them suitable candidates for the development of sustainable food packaging. Other characteristics of natural fibers, i.e., low cost, easy availability, and low impact on the environment, making these materials a promising option for food packaging. The primary focus of this study is to utilize multivariable analysis, an analytic hierarchy process and a multi-criteria decision analysis to select appropriate natural fiber reinforcement for food packaging from commonly used plant fibers (coir, date palm, hemp, sisal, jute, flax, corn stalk, banana, bamboo, cotton). The multivariable selection system is used to compare crucial food packaging materials' requirements and production parameters gathered different properties including density, Young modulus, elongation to break, moisture content, thermal conductivity, cost, availability, etc, to help identify appropriate natural fibers. From the results, selecting the most appropriate natural fiber depends on the design requirements, cost, and availability; all these parameters are also affected by the geological conditions and customer needs. Single parameter comparison is used to compare the investigated natural fiber; then analytic hierarchy process is used to rank the highest priority parameters for the natural fiber selection process. The results showed that density (22%), cost (13.6%), moisture content (11.7%), thermal conductivity (10.7%), elongation at break (7.7%), and Young modulus (7.4%) are rated in the order of priority. Hemp, banana and sisal fibers are ranked as the best choices for the food packaging by the multi-criteria decision analysis, i.e. TOPSIS. Examples are presented considering the multivariable analysis using radar charts to identify the best natural fibers source for countries such as Kingdom of Saudi Arabia, Pakistan, Bangladesh, and India. Date palm is a preferred natural fiber source for food packaging reinforcement in Saudi Arabia and Pakistan, whereas bamboo and jute are better choices for India and Bangladesh.

1. Introduction

To meet the demands of an ever-growing population, processed foods have become very common. Within the domain of the plastic packaging market, food packaging is among the fastest-growing sectors. Foods may have a wide pH range and salt contents; therefore, can reduce the life of the materials used in the food industry [1]. There are other challenges such as corrosion protection that should be achieved for direct or indirect food

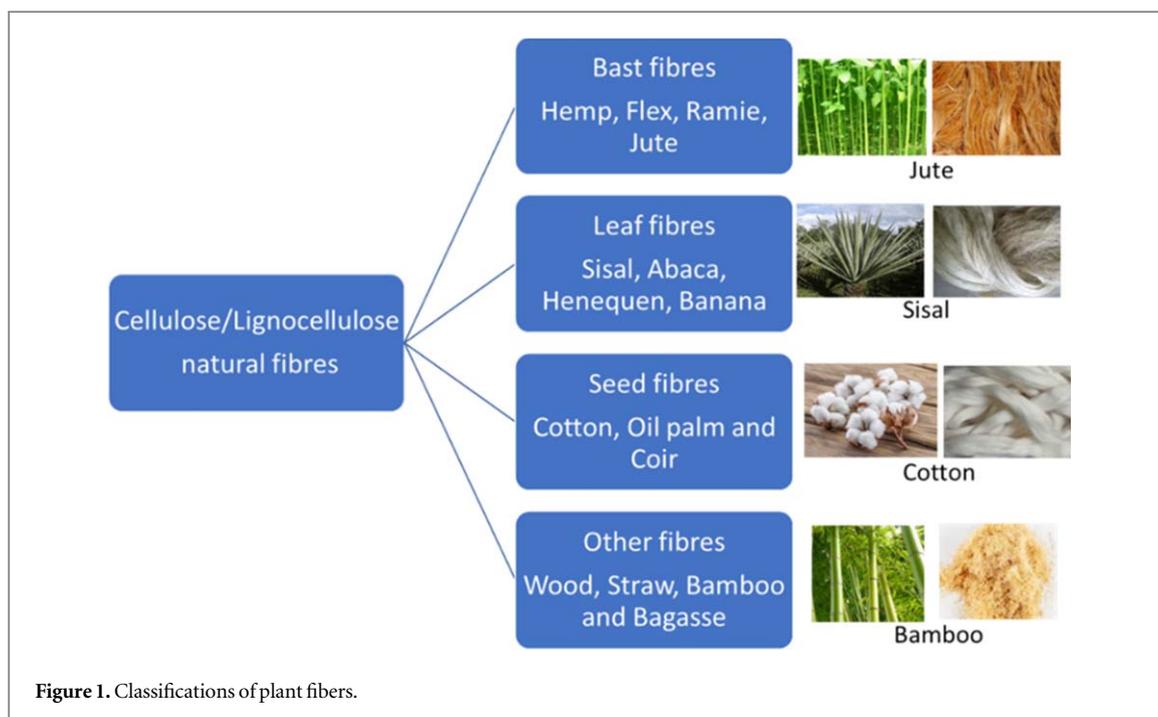


Figure 1. Classifications of plant fibers.

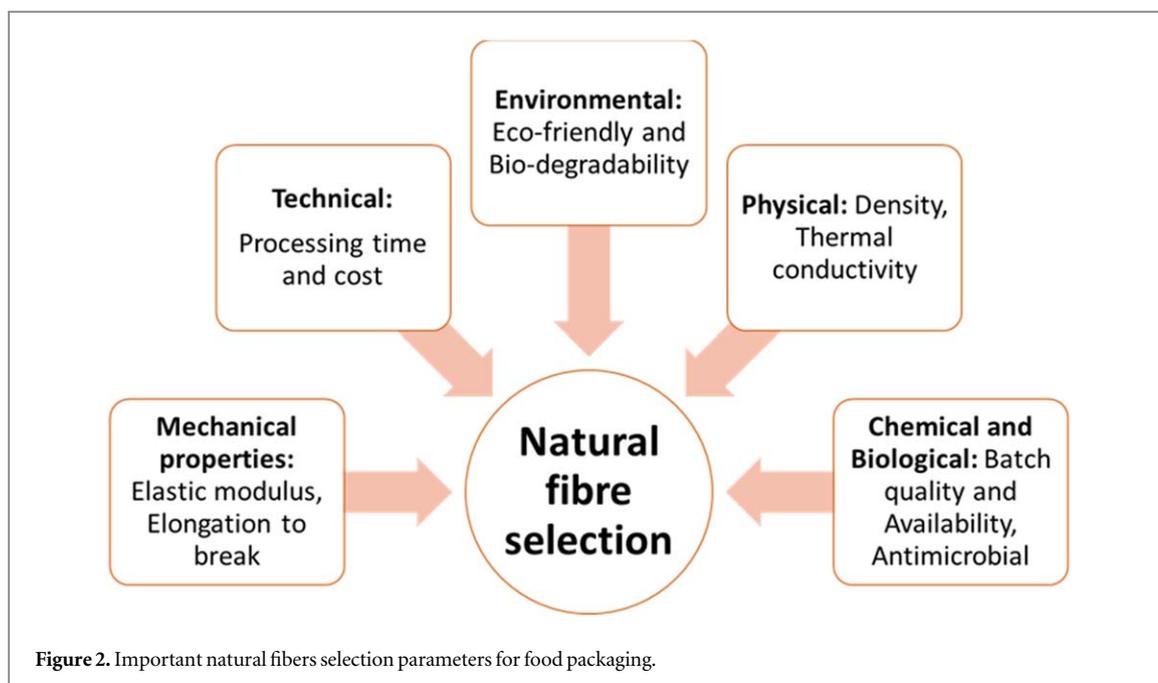
contacts utilizing materials that satisfy the rigorous constraints [2]. Therefore, polymers are getting more attraction in the industry as of their added features such as health-friendly features, improved mechanical strength, increased corrosion resistance, easier fabrication, forming, and weldability [3–6]. The packaging industry has a major portion of global polymers market, for example it was 46% of the total market in 2016 [7].

Although polymers possess high performance and great versatility for food packaging applications, yet they are barely used alone due to their intrinsic absorbency to gases and vapors [8, 9]. To tackle this limitation, many researchers have recently focused on developing compatible fillers to make polymeric composites with improved properties. It is a well-established fact that nanofillers improve mechanical properties and overcome barriers to water vapors and gases [10]. As nanofillers have less material consumption, they are useful in reducing production costs [11, 12]. Natural fibers can be used as suitable fillers in polymeric matrix materials to reduce the cost and improve the eco-friendliness. Antimicrobial, thermal and mechanical properties can also be improved by adding natural reinforcing fibers, for example flax, sisal, hemp, kenaf, jute, etc. [13]. Combination of natural fibers and nano-fillers results in improved properties together with biodegradability [14].

The natural fibers sector is expanding rapidly due to their potential to replace synthetic fibers at a cheaper cost and enhanced properties such as sustainability, thermal isolation, acoustical insulation properties, availability, etc. [15–17]. Utilizing natural fibers can benefit the ecosystem and also economic developments for farming and countryside areas, thanks to high-value commercial applications of these insufficiently used natural fibers [18]. Natural fibers are normally categorized as animal origin, mineral, and plant origin (Cellulose/Lignocellulose) [9]. Cellulose/Lignocellulose fibers, as shown in figure 1, are commonly used in polymeric composite materials. Figure 1 also provides an example from each type including jute [19], sisal [20], cotton [21], and bamboo [22]. Due to their superior properties in comparison with synthetic fibers, natural fiber composites have been applied by several researchers for different applications such as automobiles [23, 24], furniture [25], food packing [26], and construction [27].

Recent studies have focused on producing affordable bio-friendly packaging materials using natural fillers to enhance the load-carrying capacity and adding other functionalities such as thermal insulation etc. [28]. The capability of natural fiber polymeric composites is a function of the fiber and matrix materials, the interaction between fibers and matrix, antimicrobial properties, etc. [29–32]. In addition, natural fiber composites have a high tendency for water absorption, get degraded because of sunshine and microorganisms [33], which can reduce their strength and service life, making them unsuitable for many applications. As a result, there have been extensive research on treatments of natural fibers to decrease the degradation and water absorption [33].

Material selection is considered an important step to accomplish successful and sustainable designs while meeting customer satisfaction [34]. Choosing suitable natural fibers as reinforcement for food packing is therefore considered an important part in the research and development of the product [35]. For example, the natural fibers type can significantly alter the properties of the natural fiber composite packages [15, 16, 36, 37]. Various kinds of natural fiber based bio-composites have been evaluated, including corn starch [38], sugar palm



[39], empty fruit bunch [40], chitosan-kombucha tea [41], and lignocellulosic wastes fiber [42]. Figure 2 shows different factors influencing the selection process (based on extensive literature review [16, 43–46]) for different design requirements such as optimum stiffness, thermal insulation, durability, weight, price, and eco-friendly. The selection of optimum natural fiber for packaging application is complex, requiring multi-criteria decision-making methods [47–49]. Well established multi-criteria decision-making methods in other fields can be used as powerful tools for natural fiber selections. From the literature review, there is limited study on the use of multi-criteria decision-making tools for systematic selection of suitable natural fibers for food industry. The work by Salwa et al. [49] is amongst the limited works on the use of Analytic Hierarchy Process (AHP) for natural fiber selection in food packaging. Therefore, the purpose of this paper is to expand the use of multivariable analysis, AHP, and other new methods, Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and selection charts, for systematic comparison of plant based natural fibers with potential applications in food packaging. The paper also compares natural fibers to synthetic E-glass fiber, aluminum, steel and Nylon as commonly used materials. This will aid design engineers to help to choose the most suitable natural fiber through scientific knowledge, availability, and market needs. The structure of the manuscript is designed as follows: Firstly, natural fibers data is compiled under the methodology section, and then under results and discussions section parameters such as specific modulus, elongation to break, thermal conductivity, cost, availability, and multivariable analysis have been conducted to show the importance of natural fibers for food packaging. Finally, concluding remarks are presented.

2. Materials and research methodology

2.1. Natural fibers data compilation

Several natural cellulose fibers, e.g. flax, jute, and corn, have been utilized as reinforcement in starch-based bio-composites to achieve their requirements as food products [50–54]. Some natural fibers like sisal [20] and coconut coir [55], cotton [21], bamboo [22], hemp [56], date palm [57], banana [58] and flax [59]) have been utilized in other industrial applications. The compiled data from different parameters of these natural fibers that affect our decision-making process when considering a natural fiber for food packaging are provided in table 1. is listed in table 1. As natural fibers are often viewed as an alternative to glass fibers and other commonly used materials such as aluminum, steel, paper and Nylon, for comparison purposes, the characteristics of these materials are also presented.

2.2. Multi-parameter analysis

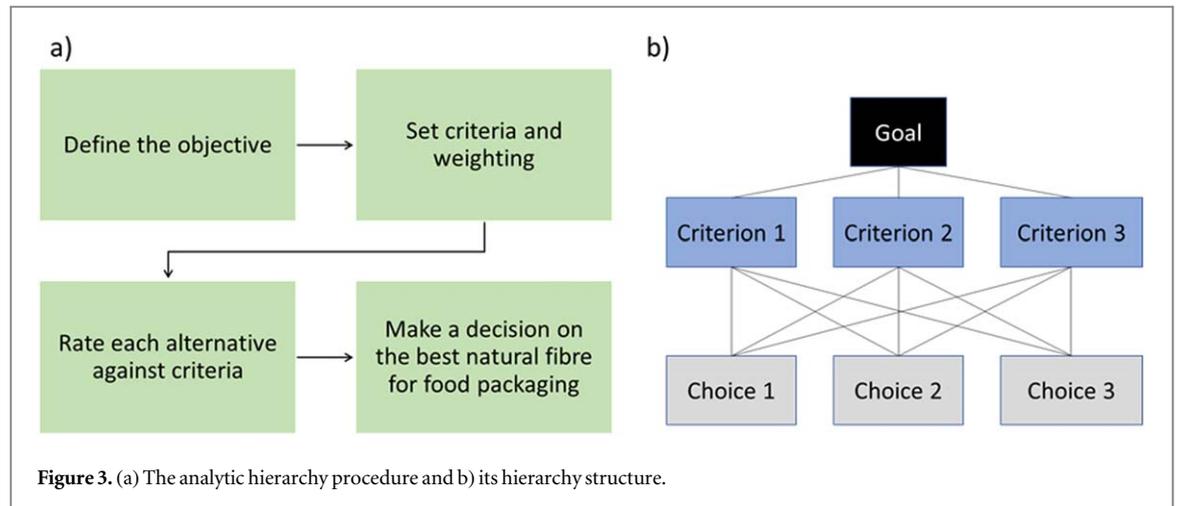
2.2.1. AHP

Screening and ranking techniques based on the materials properties and their data bank enable the designer to quickly evaluate and rank the optimal material(s) [74–76]. In this study, AHP [77, 78] is used to do a multi-variable decision-making analysis considering different factors affecting the natural fibers selection process. The

Table 1. Properties of the investigated materials [60–73].

Fiber type	Coir [64]	Date Palm [71]	Hemp [66]	Sisal [72]	Jute [61,70]	Flax [63]	Cornstalk [65]	Banana [70,72]	Bamboo [69]	Cotton [68]	E-glass [60]	Nylon [73]	Paper [73]	Steel, [73]	Aluminium [73]
Thermal conductivity ($W m^{-1} K^{-1}$)	0.047	0.083	0.115	0.07	0.036	0.055	0.49	0.09	0.042	0.05	1.2	0.25	0.066	45	220
Moisture (%)	0.2 to 8	5 to 12	6.2 to 12	10 to 22	12 to 14	8 to 12	6 to 8	10–11.5	8–10	7.7–8.7	—	0.2	4–6	—	—
Density ($g cm^{-3}$)	1.15–1.46	0.9–1.2	1.4–1.5	1.33–1.5	1.3–1.46	1.4–1.52	0.147–0.6	1.35	0.6–1.1	1.5–1.6	2.5–2.6	1.14	0.104	7.9	2.7
Specific modulus (GPa/gm^{-3})	4	7	40	17	26	55	40	9	25	6	29	4.5	30	25	25
Elongation at break (%)	15–51.4	2–19	1–3.5	2–7	1.5–1.8	1.7–2.1	1.5–3.5	1.5–9	2.5–3.7	3–10	1.8–4.8	3.5–12	5	10–30	7–25
Cost per weight ($USD kg^{-1}$)	0.3	0.02	1.2	0.5	0.37	0.25	0.5*	0.5*	0.4	1.8	2.5	3.5	0.5	0.7	2.5
Annual world production (10^3 ton)	100	4200	214	378	2300	830	750	200	30000	30000	—	—	—	—	—
Cellulose (wt %)	32–43.8	46	68–74.4	60–78	64.4	64.1	25.56	63–67.6	26–65	82.7–90	—	—	—	—	—
Lignin (wt %)	40–45	20	3.7–10	8–14	11.8	2.0	20.51	5	5–31	<2	—	—	—	—	—
Length (mm)	20–150	20–250	5–55	900	128–525	3.5–8	20–500	300–900	1.5–4	10–60	—	—	—	—	—
Diameter (μm)	10–460	100–1000	25–500	8–200	4–35	12–600	16.1–17.1	12–30	25–40	10–45	<17	—	—	—	—

* Estimated values.



factors with the highest priority values will be ranked higher and considered the most influential parameter for the natural fiber selection process [77]. As shown in equation (1), $AW = \lambda \max W$, A is matrix of the effective factors, W is the weight matrix and $\lambda \max$ is the principal eigenvalue. Thus, the eigenvector corresponding to $\lambda \max$ provides us the ranking of each factor in the ratio matrix.

$$\begin{bmatrix} 1 & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ 1/a_{1n} & \cdots & 1 \end{bmatrix} \begin{bmatrix} w_1 \\ \vdots \\ w_n \end{bmatrix} = \gamma \max \begin{bmatrix} w_1 \\ \vdots \\ w_n \end{bmatrix} \quad (1)$$

Different steps of the AHP are illustrated in figure 3, and are summarized below:

- Step 1.** Defining the objective of the decision-making process.
- Step 2.** Defining criteria and make pair wise comparisons between each criterion
- Step 3.** Create priority amongst criteria using pairwise comparison.
- Step 4.** Compare the relative weights to make a decision.

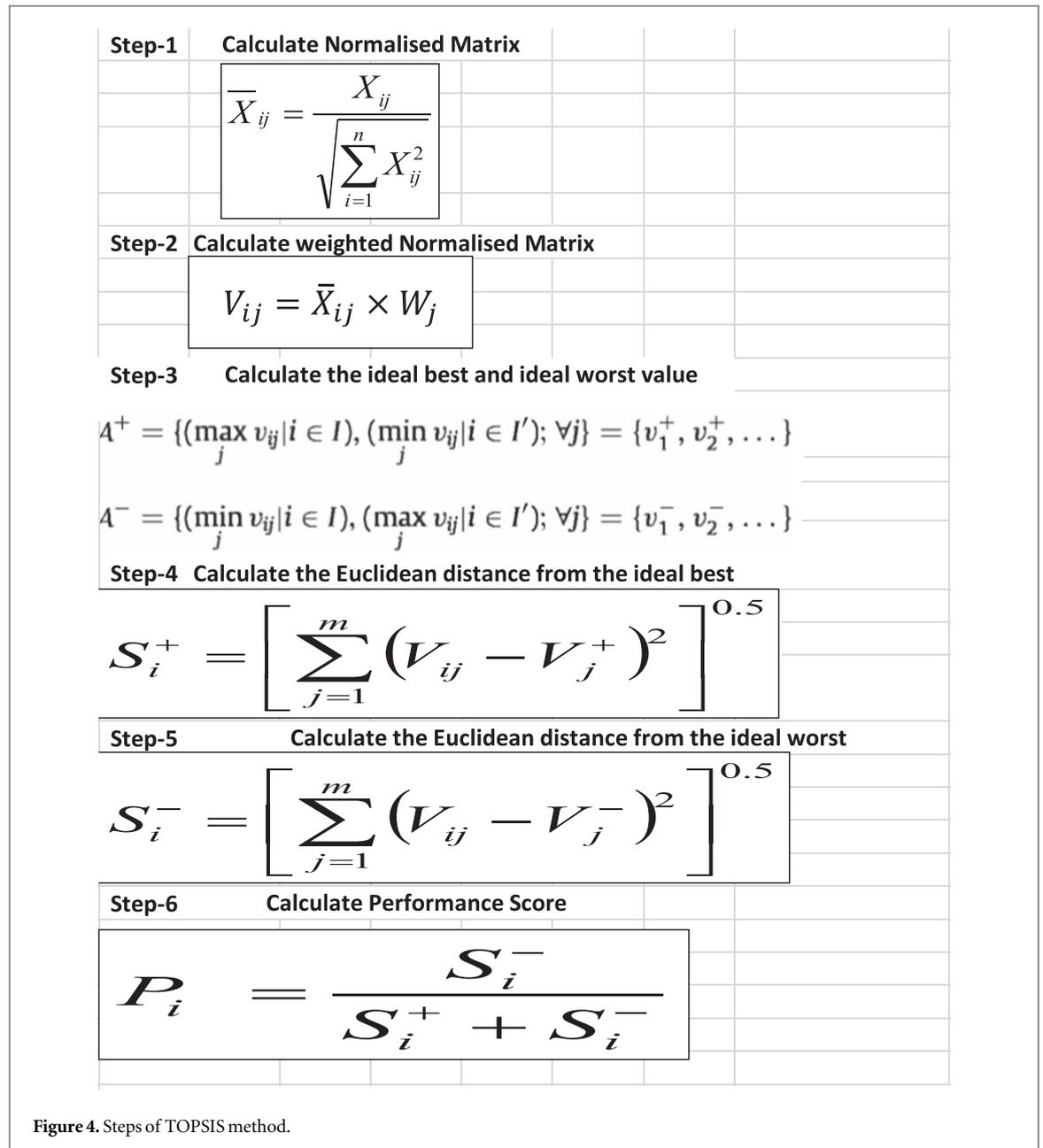
2.2.2. TOPSIS

In this method the best alternative has the longest distance from the negative ideal solution and the shortest distance from the positive ideal solution [79]. As illustrated in figure 4, TOPSIS has the following steps:

- Step 1.** Defining the normalized decision matrix (\bar{X})
- Step 2.** Determining a weighted normalized decision matrix (V)
- Step 3.** Determining ideal solution matrix of positive and negative ideal solution matrix (A)
- Steps 4 and 5.** Determining the distances between the weighted value to the positive ideal solution and the negative ideal solution.
- Step 6.** Calculating performance scores (P) for each alternative.

2.2.3. Radar charts

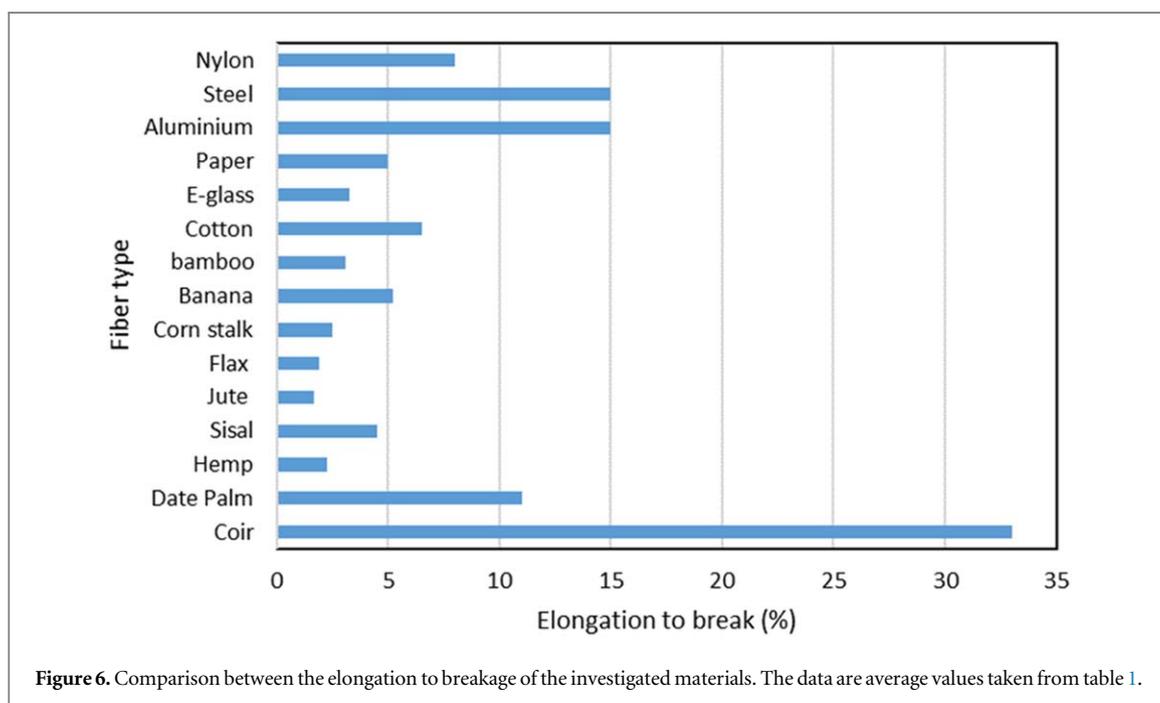
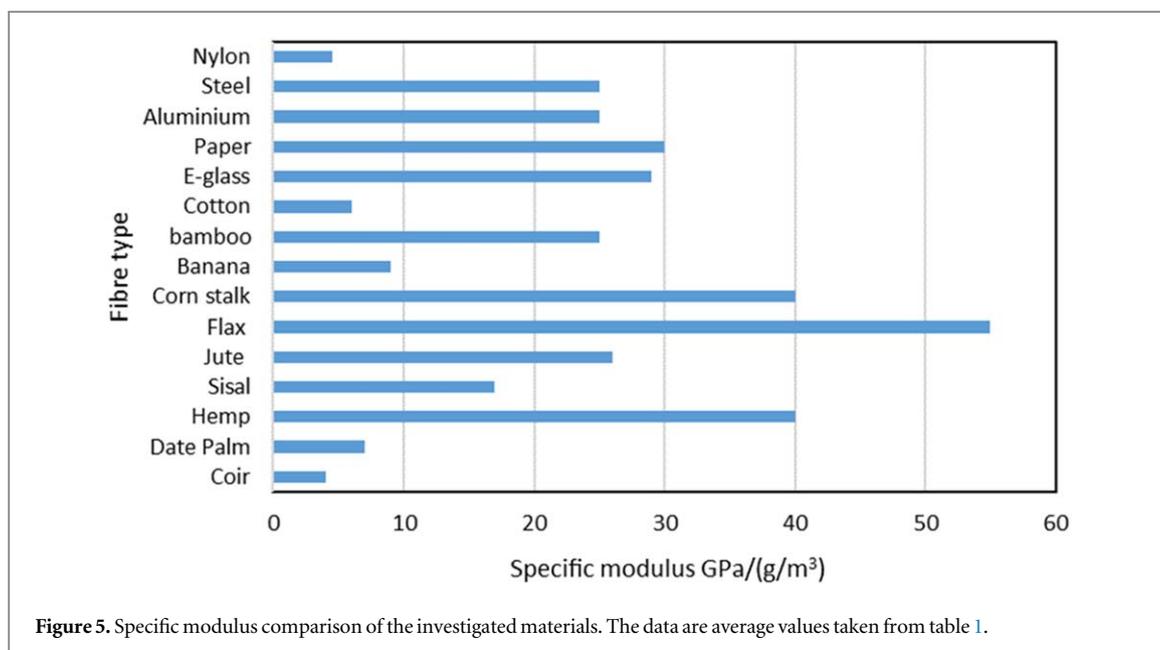
Are then used to assign different weight factors for the investigated parameters related to the food packaging performance to consider the main factors to identify the best natural fibers for countries such as Kingdom of Saudi Arabia and India. The radar charts provide a simple visual tool to compare different factors importance concurrently. Two-dimensional charts of three or more parameters are presented.



3. Results and discussions

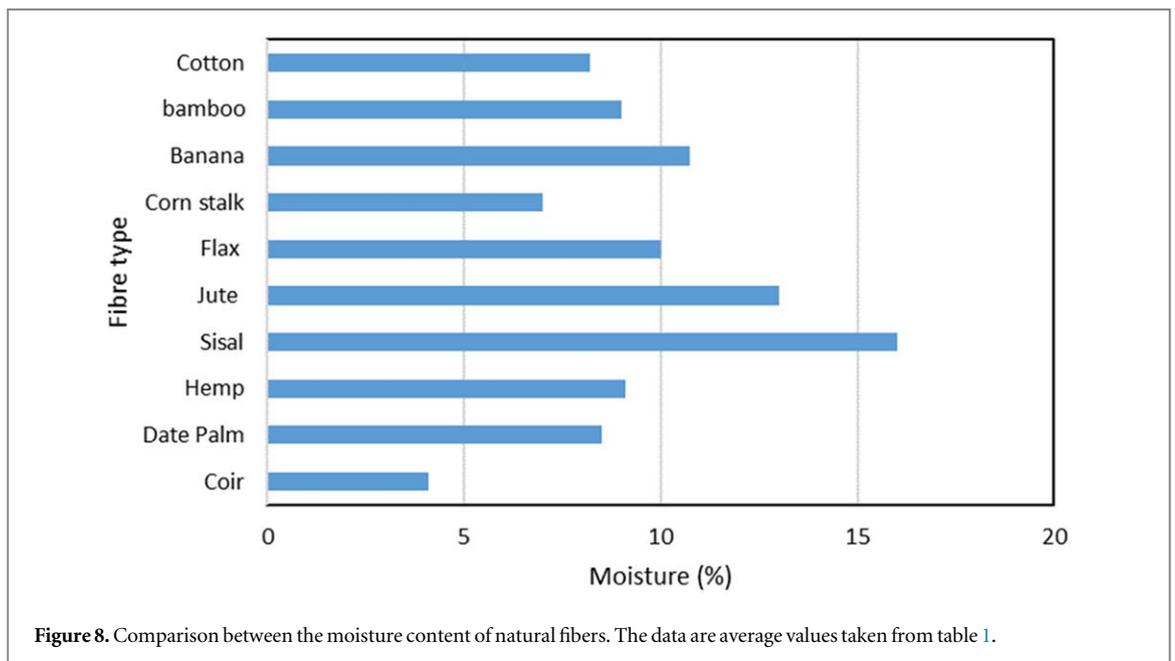
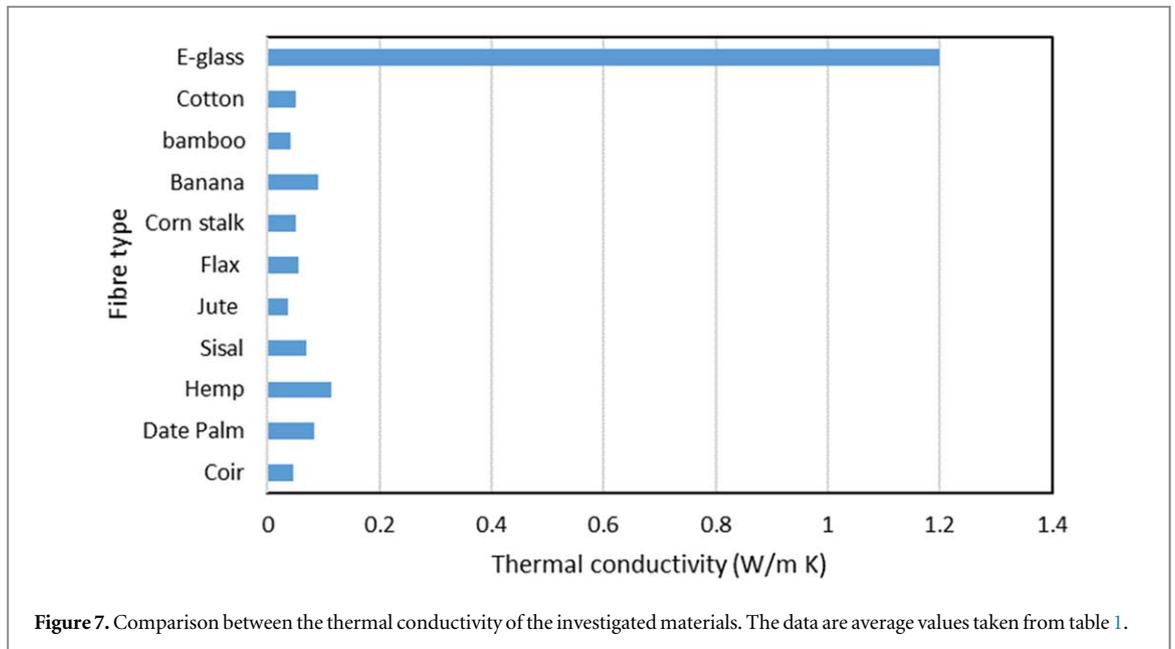
3.1. Mechanical properties: comparing specific modulus and elongation to break

Figure 5 compares the specific modulus of the materials listed in table 1. From figure 5, some natural fibers like flax, corn, and hemp have a higher specific modulus than E-glass, steel and aluminum. Figure 6 shows the elongation to breakage, where most of the natural fibers outperform the E-glass, steel and aluminum. These are desired properties of natural fibers as they lead into lower weight and stronger materials that can replace the conventional materials, which contribute toward decreasing energy consumption required for these commercial materials production, and thus increase the sustainability. Having a higher specific modulus means that the food packaging can be stiffer, or thinner and therefore lighter for a required stiffness. Stiffer natural fibers, i.e., flax would be more potent against external loads, compared to natural fibers with a lower specific modulus such as coir. This is very crucial whereby changing the fibers type or density, the mechanical properties can then be modified for specific needs. In contrast, coir has the highest elongation to break value, making it suitable when high elongation and high energy absorption are required. This means that when choosing the natural fibers based on their mechanical properties, the effect of both specific modulus and elongation to break must be considered, and the decision lies on the design requirement for the food packaging.



3.2. Physical property: thermal conductivity and moisture

Figure 7 shows natural fibers have inferior thermal conductivity when compared with E-glass. This is a very important property for food packaging. Natural fibers can be applied to develop high thermally stable insulator food packaging by improving thermal conductivity through the insulative natural fillers addition. This is because of the hollow structure of the natural fibers that provides superior insulation [80]. The other natural fibers also pose such hollow structures in different forms and sizes. It is clear from figure 8 that jute and bamboo fibers have less thermal conductivity when compared with other fibers. Therefore, they are better choices for thermal insulation. Figure 8 shows moisture content for different natural fibers, where Coir has the least and Sisal has the maximum moisture content. Both thermal isolation and low moisture content in food packaging significantly impact selecting appropriate packaging materials. For example, in a high moisture content environment, mold and bacterial growth can lead to spoilage and food-borne illnesses [81]. Furthermore, higher environmental temperatures can break down vitamins and decrease the nutritional value of food if not protected.

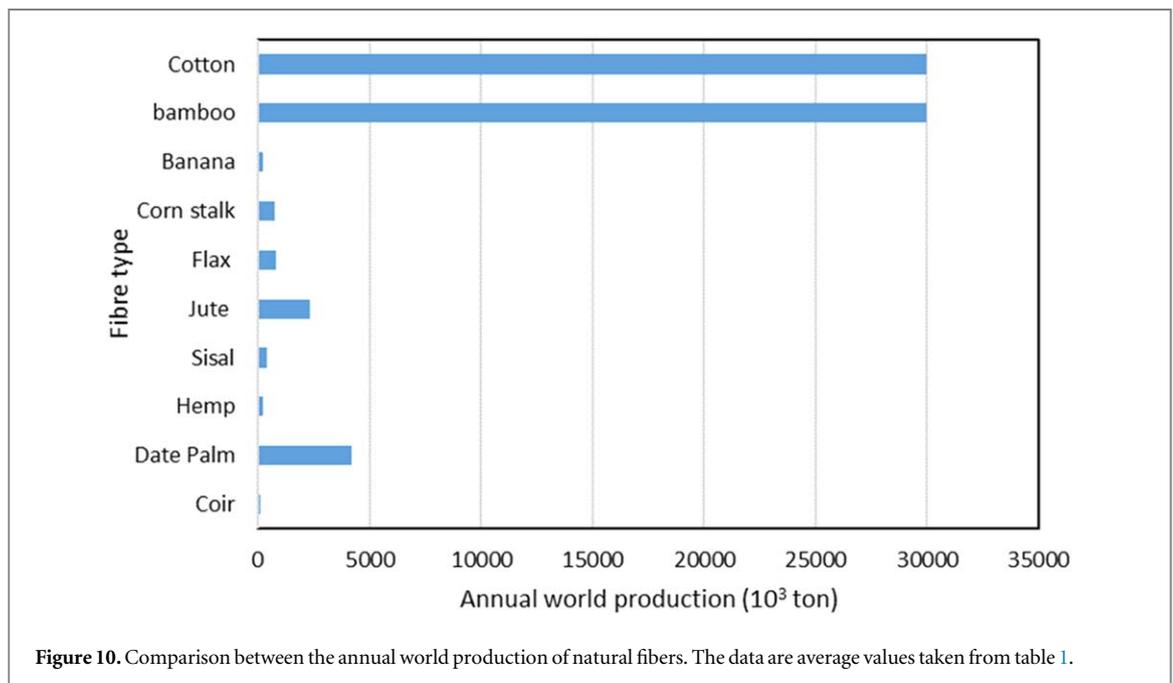
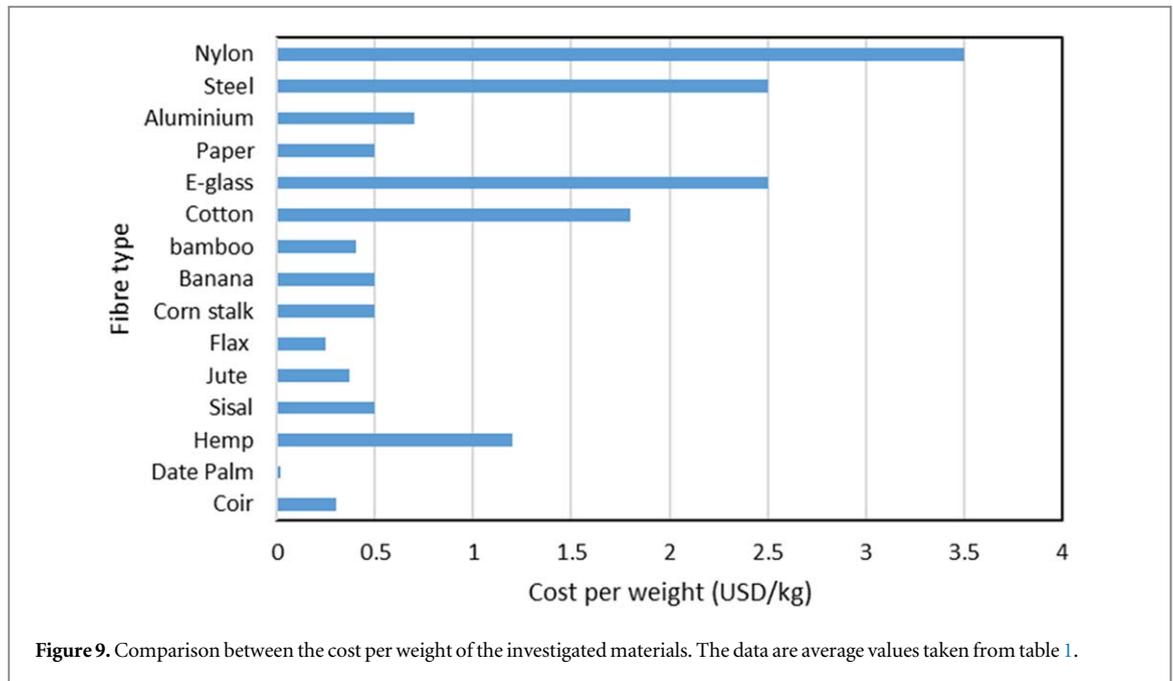


3.3. Cost analysis

It is of vital for any design to accomplish success at minimum cost value. Figure 9 compares the cost per weight of the investigated materials. All the natural fibers need lower cost to produce than E-glass, aluminum, steel and Nylon. Given the tremendous positive environmental impact and lower recycling costs, natural fibers offer a more sustainable option than synthetic fibers to meet the desired characteristics with minimal costs and resources. The date palm is the cheapest natural fibers source, while cotton is very expensive. Therefore, big variations in the costs of the natural fibers, and the cheapest the fibers, the better it is. However, the cost is just one parameter, and a multiparameter analysis should be done before selecting a fiber type for a specific design requirement.

3.4. Availability

The annual production of different natural fibers is presented in Figure 10. It is clear from the figure that bamboo and cotton fibers are abundantly available among other types; after them, date palm and jute have the highest availability. This is with no doubt an important factor that affects the utilization of natural fibers in industry. The raw material must be accessible before the manufacturing stage. Another important factor for



availability is the geographical location, which should be considered carefully when selecting appropriate natural fibers.

3.5. Multivariable analysis

AHP [77] is used to rank the highest priority parameters for the natural fiber selection process [77]. A matrix (see table 2) is built employing researcher judgment by giving each parameter a score from 1 to 9 compared with the other parameters to show the priority levels. An online AHP priority calculator [82] is used to produce priority values for each parameter as presented in figure 11. The weights are calculated using the principal eigenvector of the decision matrix. Number of comparisons = 55, Consistency Ratio CR = 2.5%, Principal eigenvalue = 11.385, Eigenvector solution: 4 iterations, and delta = 7.3E-8. Density, cost, availability, moisture content, thermal conductivity, elongation at break and young modulus are ranked in order of importance.

Table 3 reports the weighted normalized decision matrix (V) and ideal solution matrix of positive and negative ideal solution matrix (A) in TOPSIS. The weight factors are extracted from the AHP results.

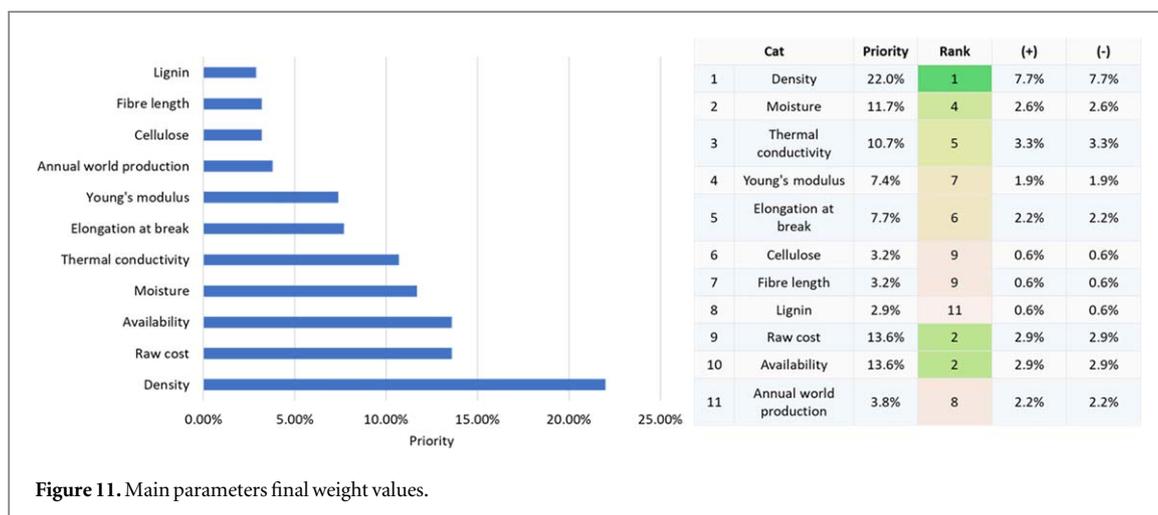


Figure 11. Main parameters final weight values.

Table 2. Comparison Matrix for the Absolute Scale

	1	2	3	4	5	6	7	8	9	10	11
1	1	3		3	4	4	5	5	6	1	6
2	0.33	1	1	2	2	3	3	4	1	1	4
3	0.33	1	1	2	2	3	3	4	1	1	1
4	0.25	0.5	0.5	1	1	3	3	4	0.5	0.5	2
5	0.25	0.5	0.5	1	1	3	3	4	0.5	0.5	3
6	0.2	0.33	0.33	0.33	0.33	1	1	1	0.25	0.25	1
7	0.2	0.33	0.33	0.33	0.33	1	1	1	0.25	0.25	1
8	0.17	0.25	0.25	0.25	0.25	1	1	1	0.25	0.25	1
9	1	1	1	2	2	4	4	4	1	1	4
10	1	1	1	2	2	4	4	4	1	1	4
11	0.17	0.25	1	0.5	0.33	1	1	1	0.25	0.25	1

Table 4 summarizes the distances between the weighted value to the positive ideal solution and the negative ideal solution. Performance scores (P) and associated rankings for each alternative are also shown in table 4. From table 4, hemp, banana and sisal are ranked as the best choice for the food packaging purpose.

figure 12 shows a multivariable analysis of the natural fibers. This multivariable analysis is a handy tool to select the materials compared to each other and consider the different parameters that are important for food packaging material selection. For example, looking at figure 12, hemp has the highest thermal conductivity, relatively high cost, low production rate, low elongation, and high specific modulus. When considering selecting the right natural fibers source, the geographical location (availability) is very important. The availability will also significantly affect the cost, which is a key consideration in any industry [76]. The annual production of the natural raw fibers is not constant and varies in different seasons and from type to type [50].

For example, India is one of the leading producers of cotton (6.5 million tons each year) and jute (2 million tons each year) globally [83]. India also has good bamboo fiber sources. Bangladesh has also an abundance of Jute (33 percent of the total worldwide production) and Bamboo [84]. So, a radar chart, like figure 13, provides a simple visual tool to select the best fiber type between these three natural fibers. From figure 13, even though cotton has high availability, it is quite expensive and has low specific stiffness, therefore bamboo and jute would be better choices. On the contrary, a great source of date palm does exist in Saudi Arabia (1.2 million tons each year) [85] and Pakistan (1.2 million tons each year) [86]. Therefore, the date palm would be a good choice in these countries. A low-cost natural fiber for food packaging, and potentially other applications, in these countries would have positive economic impacts by building new industrial opportunities to manufacture and convert the fibers which will generate jobs and help reduce poverty, provide new supply chains for materials, and generate export opportunities.

3.6. Other parameters to consider when selecting natural fibers

Figure 14 summarizes important parameters that play an important role in selecting natural fiber composites for food packaging. These include not only natural fiber properties that are discussed in detail in this work, but also matrix and composite properties. Other specific properties such as eco-friendly, antimicrobial, and bio-

Table 3. Weighted normalized decision matrix (V) and ideal solution matrix (A) in TOPSIS.

Weight	0.22 Density	0.136 Raw cost	0.136 Availability	0.117 Moisture	0.107 Thermal conductivity	0.077 Elongation at break	0.074 Young's modulus	0.038 Annual world production
Coir	0.0418283	0.008970887	0.000318403	0.071007681	0.041059772	0.070102648	0.068437027	8.89654E-05
Date Palm	0.0541776	0.1345633	0.013372906	0.034250764	0.023250714	0.022171018	0.016710627	0.003736547
Hemp	0.039232	0.002242722	0.000681381	0.031992472	0.01678095	0.004750932	0.004944981	0.000190386
Sisal	0.0402024	0.005382532	0.001203561	0.018195718	0.027568704	0.009501865	0.00965124	0.000336289
Jute	0.0415229	0.007273692	0.007323258	0.02239473	0.053605814	0.003484017	0.003426247	0.002046204
Flax	0.0389633	0.010765064	0.002642741	0.029113149	0.035087442	0.004011899	0.00420456	0.000738413
Cornstalk	0.1723831	0.005382532	0.002388019	0.041590213	0.003938386	0.005278814	0.001250455	0.000667241
Banana	0.0421381	0.005382532	0.000636805	0.027081999	0.021442325	0.011085509	0.010742546	0.000177931
Bamboo	0.0669252	0.006728165	0.095520754	0.032347944	0.04594784	0.006545729	0.003993878	0.026689622
Cotton	0.0367009	0.001495148	0.095520754	0.03550384	0.038596186	0.013724916	0.015270709	0.026689622
V+	0.0367009	0.001495148	0.000318403	0.018195718	0.003938386	0.003484017	0.001250455	8.89654E-05
V-	0.1723831	0.1345633	0.095520754	0.071007681	0.053605814	0.070102648	0.068437027	0.026689622

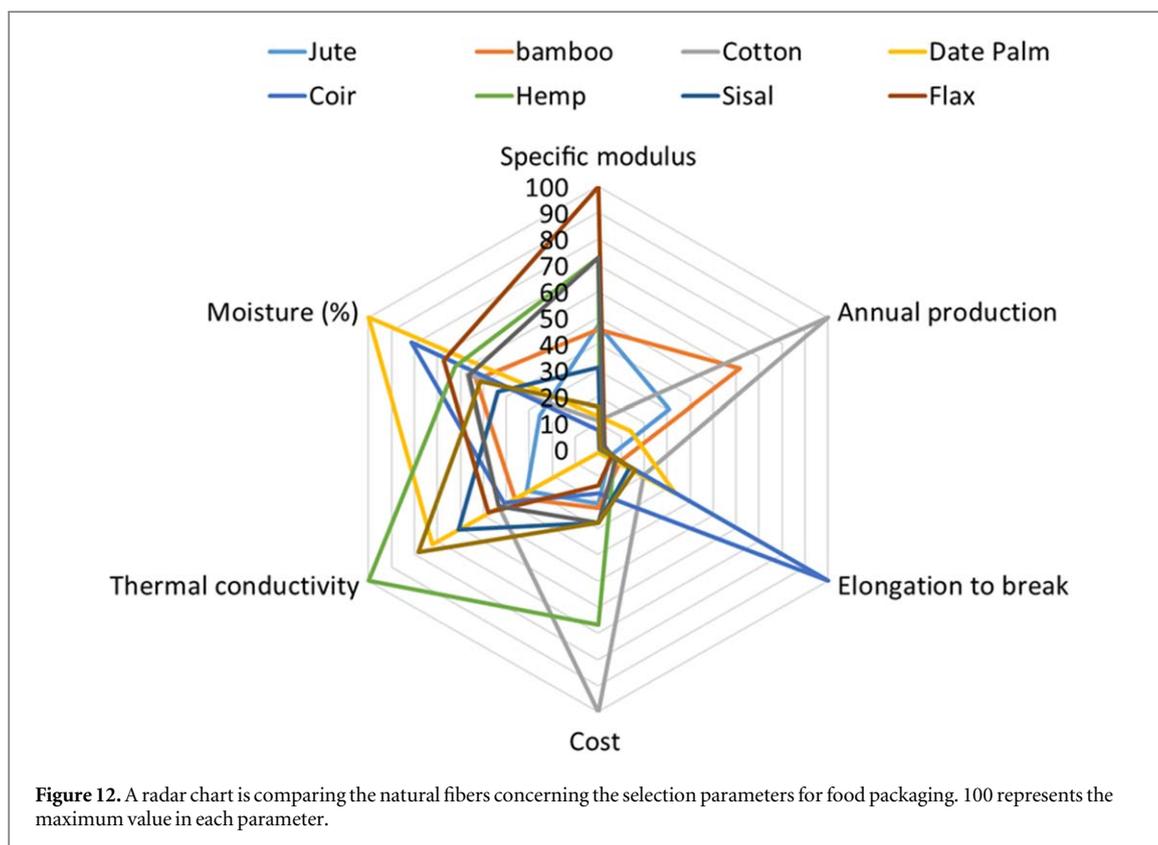


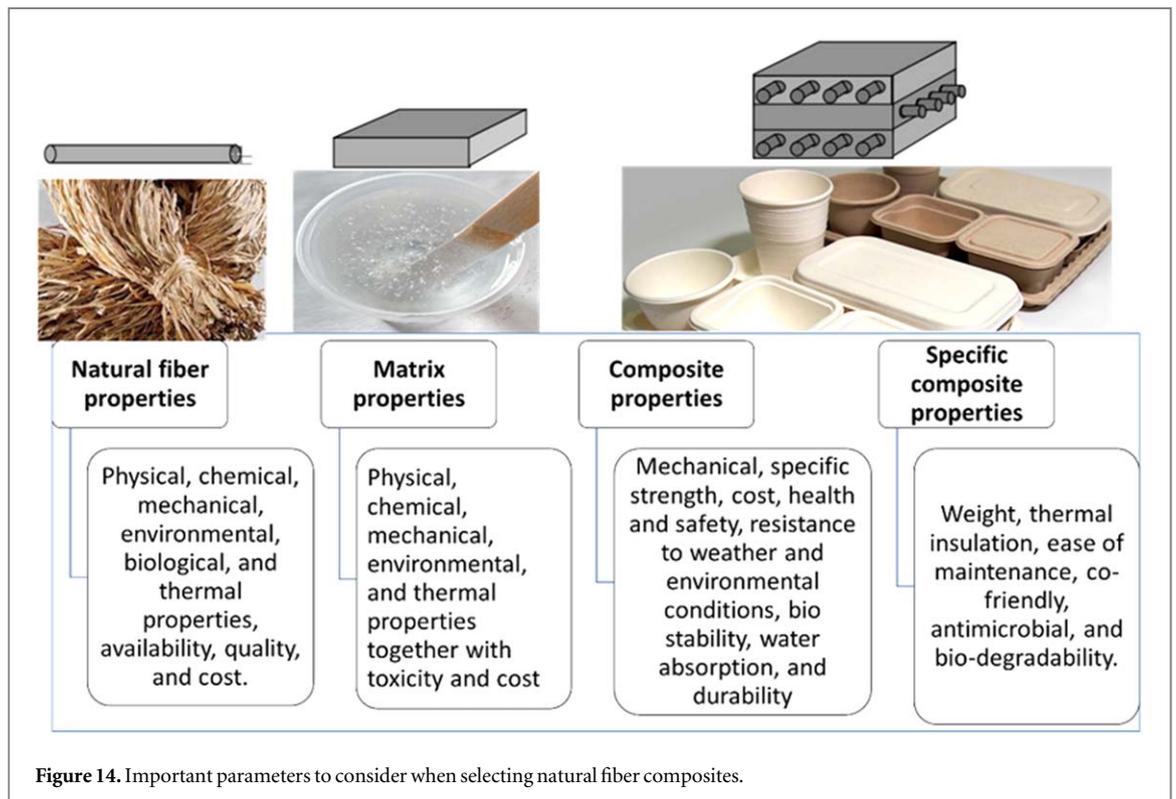
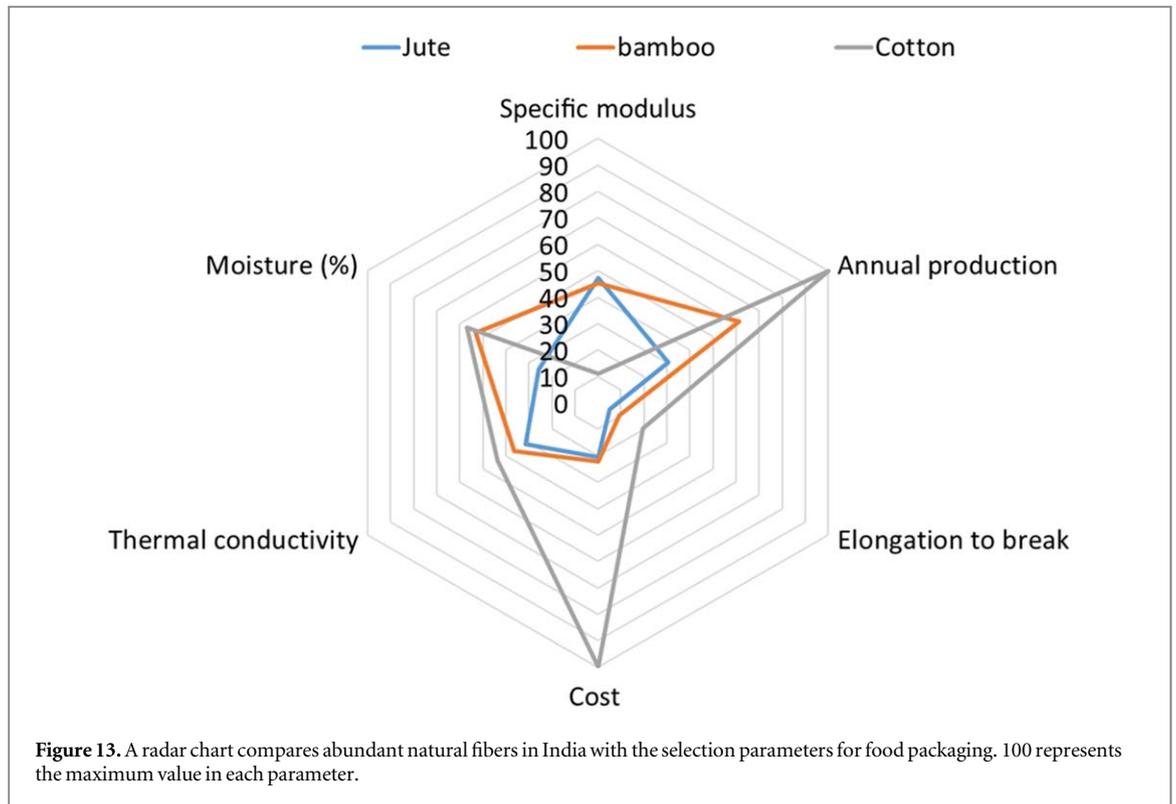
Table 4. Performance scores and associated rankings for each alternative in TOPSIS.

Si+	Si-	Pi	Rank	
0.114897147	0.206752304	0.64278768	7	Coir
0.139338587	0.168799396	0.547804571	9	Date Palm
0.01943306	0.236886077	0.924184124	1	Hemp
0.026332424	0.233119925	0.898507669	3	Sisal
0.050978048	0.229653636	0.818345359	5	Jute
0.034573594	0.230257512	0.869450403	4	Flax
0.177554924	0.195158774	0.52361578	10	Cornstalk
0.024042052	0.230505759	0.905549956	2	Banana
0.112667454	0.192895867	0.631279522	8	Bamboo
0.107579089	0.208824598	0.659994199	6	Cotton

degradability properties of natural fiber composites [32, 87] are also important factors in food-packaging. Antimicrobial agents in natural fibers are useful in delaying or even in preventing the micro-organisms growth on the product surface and, consequently, result in increased shelf life and/or improved food packaging safety. Water bioavailability will affect the biodegradation processes, which encourage microbial attack and hydrolysis of the matrix. The microbial growth depends on the water intake of natural fibers; the higher the water intake, the higher the microbial growth. The biodegradation rate depends on temperature, humidity, and type of microbes; if all these three conditions exist simultaneously, the degradation process will speed up [88].

4. Conclusions

When selecting natural fibers for food packaging, several factors should be considered based on the design requirements. These factors include mechanical properties, thermal conductivity, biodegradability, cost per weight, production rate, and geographical location. This work compared these selection factors for some commonly used plant fibers, including coir, date palm, hemp, sisal, jute, flax, corn stalk, banana, bamboo, and cotton. The fibers were also compared with E-glass, steel, aluminum and Nylon, and it is successfully demonstrated that the natural fibers can outperform these commonly used materials in most of the selection



factors, plus having the advantage of being a sustainable product. Besides, the AHP and TOPSIS that are multiparameter selection approaches and radar charts were utilized to compare the selection factors simultaneously. The suggested multiparameter analysis and radar chart are useful tools for selecting appropriate natural fibers and can help to make a systematic decision-making process. Using the results for example it is concluded that due to the resource efficiency and other excellent properties, date palm is a preferred natural fibers source for food packaging reinforcement in Saudi Arabia and Pakistan. In contrast, bamboo and jute are better choices for India and Bangladesh.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Author Contributions

Conceptualization, H.T.A. and M.F.; project administration, methodology and analysis, A.H.A., B.F.F and K.A.E.A; writing—original draft preparation, D.S., E.M.A. and M.M.; supervision, writing—review and editing, H.T.A. and M.F. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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