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Research article

Determining the appropriate natural fibers for intelligent green wearable devices made from biomaterials via multi-attribute decision making model

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ABSTRACT

Intelligent and green wearable technology becomes essential for new modern societies. This work introduces a multi criteria decision making model to properly assess and compare relative desired criteria for selecting the most suitable constituents for green body wearable bio-products made from bio-based materials. It aims to enhance the sustainability of intelligent green wearable devices by providing support in the selection process of lightweight, eco-friendly materials suitable for personal body wearable bio-products made of natural fiber composites to improve qualities that may help in better monitoring human vital signs and thereby address the health care concern. The relative intrinsic characteristic and merits of various natural fibers were utilized to compare and evaluate their relative performance in bio-composites. The model considered several evaluation factors like mechanical performance including tensile strength and modulus of elasticity, comfortability including size and weight, availability, fiber orientation, cellulose content, and cost. Results have demonstrated different priorities of the considered natural fibers relative to each evaluation factor. However, the model was capable of properly evaluating and ranking the best fibers relative to the whole conflicting evaluation criteria simultaneously. The closeness of priorities in several cases emphasizes upon using such decision making models to be able to judge the relative merits of natural fibers for such applications. It can also help designers to avoid bias during determining the best alternatives considering several conflicting evaluation criteria.

1. Introduction

The introduction of intelligent and green wearable technology has significantly simplified our lives. The current trend in clothing technology and wearable devices is the demand for creative apparel. Smarter type of clothing and wearable appliances allow for the tracking and observation of an individual's movement, and physical well-being [1,2]. It also facilitates monitoring vital signs such as

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heart rate, blood pressure, and body temperature. Green wearable appliances, such as watches, sensors, temperature controllable clothes and bands, have become a familiar sight in recent times [2,3]. These gadgets represent a significant leap forward in the realm of human well-being as they enable the continuous monitoring of one's health. The biological information gleaned from these wearables has the potential to identify and prevent diseases at their initial stages, while also offering valuable suggestions for leading a healthier life [4,5]. However, there exists a considerable population who harbor reservations towards embracing the current repetition of wearables due to their inherent discomfort. Take, for instance, those who find wristwatches bothersome as the perspiration resulting from wearing them can agitate their delicate skin [6,7]. Undoubtedly, the level of comfort associated with these devices plays a pivotal role in determining their widespread adoption within the realm of next-generation healthcare monitoring. Various elements that can enhance the pleasantness of wearing in order to create future wearable devices that will be embraced by all individuals have been discovered. One of these elements is the mechanical attributes [8,9]. Numerous existing wearables possess inflexible and diminutive physical forms due to their composition of traditional electronic materials.

In contrast, skin is pliant and capable of assuming diverse shapes. However, the incongruity in mechanical properties can cause a sensation of unease when using several wearables. Recently, there have been advancements in the development of soft and stretchable electronic materials that can match the mechanical characteristics of our skin [10,11]. When appropriately attached, these materials enable the application of devices onto the skin, aligning with its contours, without impeding the wearer's activities. However, certain electronic components, such as silicon circuits and batteries, are not easily amenable to being fashioned from appropriate materials. Thus, soft, comfortable and reasonably strong materials like bio-composites have to be properly considered for the personal body wearable devices.

Bio-composites made of natural fibers have certain distinct advantages over those made of synthetic fibers, including being more lightweight, cheaper, recyclable, and environmentally benign [12,13]. The poor impact strength, low thermal stability, and high moisture absorption qualities of natural fibers, despite their advantages in the creation of composites, have a negative impact on their long-term service behavior and restrict their usage in harsh outdoor applications [14–16]. The hydrophilic characteristic of natural fibers is what causes the high moisture absorption behavior in natural fiber composites. This could cause the fibers to swell, ultimately weakening the composites' mechanical strength and dimensional stability [17–19]. The decline of flexural, impact, hardness, and fracture toughness qualities in cotton fabric composites was caused by moisture absorption [20,21]. As an alternative, hybrid composites of natural fibers and/or mixed with synthetic fibers to improve composite mechanical performance and water resistance have been produced. Extensive research has been conducted on natural fiber reinforced hybrid composites, including examinations into long- and short-term characteristics in order to discover viable application areas for the composites [22,23]. Table 1 shows several hybrid composites and their manufacturing process [24–27]. Hybrid composites were found to have improved fatigue characteristics and a longer fatigue life, making them suitable for semi-structural applications.

In order to enhance the performance of bio-composites, it is imperative to possess a comprehensive understanding of their physio-chemical and mechanical aspects. This is primarily because the characteristics of bio-composites are heavily reliant on the type of matrix, fiber, and the interfacial bonding that exists between them [28,29]. Thus, the adhesion between the matrix and the naturally reinforcing fibers plays a pivotal role in determining the mechanical properties of the bio-composite. This is so as the efficiency and compatibility of the reinforcement are determined by the transfer of stress between the matrix and the reinforcing fibers [30,31].

Furthermore, it is widely believed that there exists an increasing necessity for the implementation of decision-making models, along with other advantageous instruments, with the aim of enhancing the attainment of more sustainable societies. However, a systematic decision-making model that can effectively utilize the available data sets as well as the expertise of professionals to anticipate the suitability of a particular natural fiber type for the reinforcement of biomaterials to produce green personal wearable devices has yet to be developed. The Analytical Hierarchy Process (AHP) is a tool used for analyzing multi-criteria decision-making (MCDM) problems. It is used in wide range of applications to appropriately select the most suitable alternatives among several available considering various

Table 1
Natural fiber reinforced hybrid composites.

Natural Fiber	Matrix	Hybrids	Process
Sugar palm fiber	Thermoplastic polyurethane	Roselle fiber	Hot press
Sugar palm fiber	Cassava starch	Cassava fiber	Casting
Sugar palm fiber	Polypropylene	Kenaf fiber	Compression molding
Sugar palm fiber	Cornstarch	Cornstalk fiber	Solution casting
Sugar palm fiber	Epoxy	Ramie fiber	Compression molding
Sugar palm fiber	Vinyl ester	Roselle fiber	Hand lay-up
Sugar palm fiber	Polypropylene	Glass fiber	Film stacking and hot compression
Kenaf fiber	Epoxy	Bamboo fiber/nanoclay	Hand lay-up
Kenaf fiber	Epoxy	Kevlar	Hand lay-up
Hemp fiber mat	Green epoxy	Sisal fiber	Hand lay-up method and hot press
Hemp fiber	Unsaturated polyester	Soybean oil/nanoclay	Compression molding
Hemp fiber	Polylactic acid	Sisal fiber	Injection molding
Hemp fiber	HDPE	Basalt fiber	Injection molding
Flax fiber	Polypropylene	Kenaf/hemp fiber	Compression molding
Flax fiber	Polylactic acid	Kenaf/hemp fiber	Compression molding
Ramie fiber	Polylactic acid	Poly (ε-caprolactone)	Compression molding
Ramie fiber	Vinyl ester	Jute fiber	Hand lay-up

simultaneous conflicting evaluation criteria and it is widely utilized in materials science [32–36]. Despite of the existence of various decision making tools including the hybrid multi-attribute decision-making ones like TOPSIS, Fuzzy-AHP, best worst method (BWM), and the regret theory based on distance from average solution (RT-EDAS) [37–40], the AHP was found in most cases better than other decision making tools due to its high reliability, simplicity, and its capability of dealing with both subjective and objective decisions with rigorous consistency index for the judgments.

Moreover, in order to circumvent the significant drawbacks associated with natural fibers, such as performance deterioration, as well as to achieve a more favorable bonding interaction between the fiber and the matrix, it is imperative to make wise decisions when selecting the appropriate natural fiber type for personal wearable devices. These decisions are crucial in order to achieve the desired characteristics and performance of the bio-composites.

Consequently, the aim of this study is to enhance the sustainability of intelligent green wearable devices by providing support in the selection process of lightweight, eco-friendly materials suitable for personal body wearable bio-products made of natural fiber composites such as clothing and wearable appliances, sensors, temperature controllable clothes, and armor vests to improve qualities that may help in better monitoring human vitals and there by address the health care concerns. Specifically, the objective is to create a decision-making model using the analytical hierarchy process to determine the most appropriate natural fiber type by maximizing the desired properties and performance of the reinforced bio-composite, which would help in selecting available natural waste materials for the advance of industrial sustainability that line up with the sustainability goals and promote cleaner production practices.

2. Methodology

In order to design a proper personal wearable devise ergonomically, factors such as mobility, weight and comfort are important. Achieving an even distribution of weight across the entirety of the human body is a key when it comes to avoiding the weariness that can plague the user. Additionally, this careful distribution ensures that no respiratory issues arise, particularly when faced with sudden fluctuations in temperature. The task of designing a personal suit of the wearable cloth becomes all the more challenging due to the need for the designer to strike a harmonious equilibrium between the level of protection required and the specific type of hazard to be faced. For instance, body armors tailored for ballistic protection must possess sufficient flexibility in their weave to prevent inconvenient failure. By adhering to these guiding principles, a personal body wearable device can be carefully designed to provide the unique needs and demands of its wearer. Therefore, to properly design personal green wearable devices made of biomaterials, several critical criteria have to be taken into account while considering the natural fibers as a major constituent for this type of materials. These may include the following.

- Tensile Strength: Personal green wearable devices are usually subjected to various modes of failure characterized by tension during the external applied loading forces. Therefore, the strength to resist tension is a crucial factor in selecting the appropriate fibers to make biomaterials suitable for personal body wearable devices. It refers to the material's ability to withstand externally applied loads that create tension in relation to its area. Generally, the tensile strength of polymers can be enhanced by incorporating fibers into the matrix. The fiber with the highest tensile strength was granted the utmost importance in the selection process. Table 2 shows the mechanical and physical properties of some natural fibers [24,41,42].
- Tensile Modulus: The measure of elasticity, known as the tensile modulus, possesses a certain importance in the selection process as it represents the stress and strain engagement within the boundaries of elasticity. This relation between stress and strain is encapsulated in the ratio that is the tensile modulus, also known as Young's modulus (E). In the field of natural fibers, the modulus of elasticity dramatically varies with fiber type and constructional constituents.
- Cellulose content: Plant fibers are natural composites because they have cellulose fibrils embedded into the lignin matrix. Cellulose is a natural substance that may be found in all natural fibers. It usually gives the natural fiber rigidity. It is a linear homopolymer composed of D-glucopyranose units connected together by b- 1, 4 glycosidic linkages. It is composed of carbon, hydrogen, and oxygen. It has been established that cellulose is made up of repeating dehydrated glucose units. Among natural fibers, cotton fibers have the maximum cellulose content value while nucifera coconut shell has minimum cellulose content [43,44]. However, the

Table 2
physical and mechanical properties of some natural fibers.

Fibers	Density (kg/m^3)	Diameter (μm)	Tensile Strength (MPa)	Tensile Modulus (GPa)	Elongation %
Sugar Palm	1290	99–311	190.29	3.69	19.6
Jute	1460	–	393–800	10–30	1.5–1.8
Sisal	1450	50–300	227–400	9–20	2–14
Kenaf	1400	81	250	4.3	–
Flax	1500	–	345–1500	27.6–80	1.2–2.3
Hemp	1480	–	550–900	70	1.6
Banana	1350	80–250	529–759	8.20	1–3.5
Coir	1150	100–460	108–252	4–6	15–40
Bamboo	910	–	503	35.91	1.4
Cotton	1600	–	287–597	5.5–12.6	3–10
Cocos nucifera	1300	–	88–196	5–9	2–14
Ramie	1500	13–126	500	44	2–2.5

highest cellulose content will increase hydrophilic properties because cellulose forms strong hydrogen bonds with water vapor in the atmosphere. Natural fibers with the least amount of cellulose cannot provide strong hydrogen bonds with neighboring cellulose molecules and with water vapors. This affects the fiber surface roughness and exhibits moderate surface interaction with the matrix in Biocomposite materials.

- Fiber orientation: The arrangement and orientation of fibers plays a crucial role in determining the performance of biomaterials made by reinforcing natural fibers with polymers. Research has shown that woven fibers exhibit superior impact performance compared to unidirectional and short fiber based composites. Furthermore, the dense and tightly woven structure of natural fibers effectively prevents perforation during impact for wearable devices. Consequently, naturally woven dense fibers are more suitable for wearable devices under impact environment like that of armor and helmets etc. Thus, cocos nucifera sheath and sugar palm fibers are preferable in such wearable devices rather than banana, sisal and coir fibers [45].
- Density: It plays a significant role in the selection of fibers for personal body wearable devices, as it directly influences the comfort experienced. The density of natural fibers has a notable impact on the strength to weight ratio of composites. This, in turn, leads to enhanced mechanical properties and superior performance. However, fibers with higher density contribute to the overall weight of the body wearable devise, negatively affecting the mobility of persons and demand more physical effort to bear. Therefore, it is crucial to find an alternative natural fiber with a density comparable to or lower than that of synthetic fibers like Kevlar in case of armor or safety vest applications (See Table 2). Therefore, density is one of the most important features of the fibers. The fiber with the lowest density is given the highest priority in the selection for personal green wearable devices, while the fiber with the highest density is assigned the least priority.
- Cost: It is one of the key factors in developing new green products. Several factors are in fact affecting the cost of product development including the cost of raw materials, cost of production, cost of quality assurance, as well as others. Consulting the literature as well as database of commercial online suppliers, the natural fiber that possesses the most affordable nature is crowned with the highest priority scale value in the selection process. Unfortunately, the criterion of "cost" is bestowed with a minimal relative intensity scale value, for it must bow to the primary design requirement of personal body wearable devises.
- Availability: A greater importance has been assigned for the value for agro wastes and abundant natural fibers due to environmental impact. However, when assigning the relative intensity value, "availability" has been granted the lowest magnitude on the scale. This decision is based on the reality that technical factors such as cellulose content, fiber alignment, compactness, and tensile strength were accorded greater importance than mere availability.
- Comfortability: It is imperative to conceptualize forthcoming wearable contraptions from a holistic standpoint to avoid direct contact between inflexible constituents and the skin. Numerous existing wearables possess inflexible and diminutive physical forms due to their composition of traditional electronic materials. Viable resolutions may entail the wireless operation of flexible devices or their conception to be self-sustaining. Additional aspects to consider in the conception of forthcoming wearables encompass the permeability to gases and the administration of thermal energy. To guarantee that the devices can be put on for extensive durations, the dermis ought to possess the capacity to respire and facilitate the dissipation of bodily heat via skin-compliant contrivances. The attraction of wearable devices extends beyond their tangible attributes. The very essence of these devices can influence an individual's inclination to don them.

The Analytical Hierarchy Process (AHP) is one of the best decision-making problem tools utilized to analyze the multi-criteria decision-making (MCDM) problem to properly select the most appropriate alternatives among several available considering various simultaneous conflicting evaluation criteria as it was introduced by Saaty [46]. This is due to its high reliability and the robust structure and the simplicity it has [47,48]. It consists of several sequential steps getting benefit of matrix algebra and solving eigenvalue of matrix forms that contain pairwise judgments. Identifying the goal of the study is the first step in AHP. The potential solutions, stated to as alternatives, are then defined. The evaluation criteria and sub-criteria are assigned next to evaluate the alternatives. This is attained by assigning weights to the sub-criteria with respect to the main one, and the main with respect to the goal, while alternatives are weighted to each sub-criterion in the model in a hierarchical manner via appropriate data if the evaluation criterion has specific data (quantitative evaluations) or experts' feedback for qualitative evaluations with consistent decision matrix called judgment matrix. AHP has been employed to analyze and solve different complex decision problems in engineering [49,50].

Table 3
Factors affecting personal body wearable bio-products material selection.

Factor	Specific requirement of personal body armor material	Corresponding natural fiber selection criteria
Mechanical performance	Tensile strength and stiffness	Tensile strength, Tensile modulus
Comfortability	Density, size	Low density enhances producing lower weight product
Fiber orientation	Easiness of fiber arrangement, the dense and tightly woven structure	fiber orientation and tightly woven structure have major roles in the impact resistance and mechanical performance of the fiber reinforced polymer composites
Cost	Raw material cost	Overall cost including extraction and raw fiber cost
Availability	In the global and local market	In the global and local market
Cellulose content	cellulose content of the natural fiber	High cellulose content of the natural fiber enhances mechanical performance and Low cellulose content of the natural fiber enhances the hydrophobic nature

Examples include determining the most fit materials and products for certain application, selecting the most appropriate energy harvesting strategy, selecting green polymeric-based composite manufacturing processes [51], making decisions for optimal reinforcement conditions of natural fiber composites as well as others [52–55].

Mathematical representation of the AHP formulation and structure is offered to build a model to address the problem of selecting the most appropriate natural fiber type among several available ones to be used as reinforcement in bio-composite material suitable for personal body wearable bio-products made of natural fiber composites. Such body wearable bio-products may include armor vest, and controlled temperature clothes, wearable sensors etc. The merits of various natural fibers including cocos nucifera (coconut sheath), hemp, ramie, banana, sugar palm, and cotton were considered to be utilized as reinforcement fibers in bio-based materials as they have relative potential characteristics regarding the considered evaluation criteria. The relative inherent characteristics of the fibers were utilized to compare and evaluate their performance in the overall considered properties of the personal wearable bio-products including their mechanical, economic and technical criteria. The factors considered in the study are tabulated in Table 3, and the hierarchical structure of AHP for the current problem is illustrated in Fig. 1. The pairwise comparisons between different elements in the hierarchy structure were performed according to the AHP intensity of importance scale as in Table 4.

Basic stage within the AHP involves the completion of the final decision matrix $[C]$, which is determined by using the geometric mean of the obtained consistent pairwise comparison matrices $[C_{PW}]$ as follows: For a general judgment of nxn matrix $[C]$ as in equation (1) contains the judgment elements as in equation (2).

$$[C] = \begin{bmatrix} C(1,1) & C(1,2) & .... & C(1,n) \\ C(2,1) & C(2,2) & .... & C(2,n) \\ C(3,1) & C(3,2) & .... & C(3,n) \\ \cdots & \cdots & .... & \cdots \\ \cdots & \cdots & .... & \cdots \\ \cdots & \cdots & .... & \cdots \\ C(n,1) & C(n,2) & .... & C(n,n) \end{bmatrix} \tag{1}$$

$$C(i,j)\Big|_{v\ \text{experts}}^{1\le i,j\le n} = \sqrt[v]{\prod_{k=1}^{v} C_{PW}(i,j)\Big|_k} \tag{2}$$

After that, normalizing matrix $[C]$ is required with respect to the sum of the entries for each column to have the normalized matrix $[C_{norm}]$ as in equation (3). Then, the average weights vector $\{W_C\}$ is calculated as in equation (4).

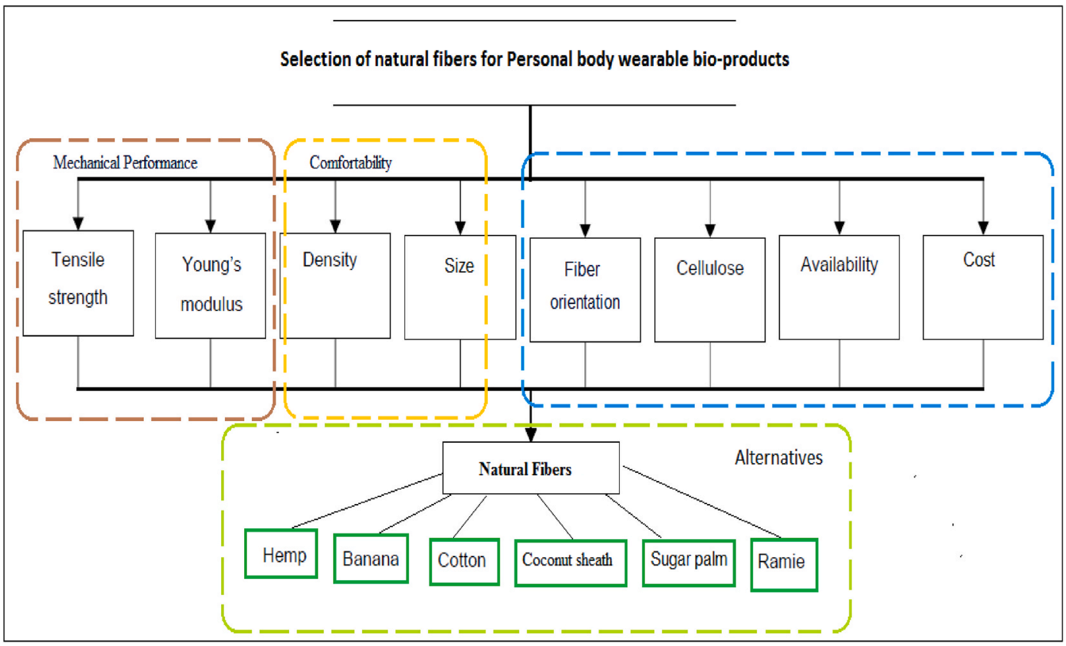

Fig. 1. Hierarchical structure of the selection model.

Table 4
AHP intensity of importance scale.

Numerical rating scale	Relative rating of two main criteria: *MCi* and *MCj* in level *k* with respect to level *k-1*.	Explanation
1	*MCi* and *MCj* have equal importance. In pairwise comparison matrix $[C_{PW}]$ with order n: $Cpm(i,j) = 1, 1 \leq i \leq n$	Experts see that two main criteria *MCi* and *MCj* contribute equally to the main goal G.
3	*MCi* is thought to be moderately more important than *MCj*.	Experts see that *MCi* is slightly more important to main goal G than *MCj*.
5	*MCi* is thought to be strongly more important than *MCj*.	Experts see that *MCi* is strongly more important than *MCj* to main goal G
7	*MCi* is thought to be very much more important than *MCj*. or is demonstrated to be more important than *MCj*.	Experts see that *MCi's* dominance over *MCj* has been demonstrated Therefore, *MCi* is strongly favored than *MCj* with respect to goal G.
9	*MCi* is demonstrated to have much more importance than *MCj*.	Experts see that there is the highest possible degree of evidence that proves *MCi* is more important to product success than *MCj*. This is considered as the highest possible order of affirmation.
2, 4, 6, 8	Intermediate values between the two adjacent judgments.	Experts use these values when the decision maker needs to compromise between two positions in the table.
Reciprocals of above scales	In pairwise comparison matrix C_{PW} with order *n*. $C_{PW}(i,j)=1/C_{PW}(j,i), 1 \leq i,j \leq n$	If criteria *MCi* has one of the above nonzero numbers assigned to it when compared with criteria *MCj*. then criteria *MCj* has the reciprocal value when compared with criteria *MCi*.

$$[C_{norm}] = \frac{C(i,j), 1 \leq i,j \leq n}{\sum_{i=1}^{n} C(i,j)} \tag{3}$$

$$\{W_C\} = \left\{ \begin{array}{c} \frac{\sqrt[n]{\prod_{j=1}^{n} C(1,j)}}{\sum_{i=1}^{n} \sqrt[n]{\prod_{j}^{n} C(i,j)}} \\ \frac{\sqrt[n]{\prod_{j=1}^{n} C(2,j)}}{\sum_{i=1}^{n} \sqrt[n]{\prod_{j}^{n} C(i,j)}} \\ \dots\dots\dots\dots\dots\dots \\ \dots\dots\dots\dots\dots\dots \\ \frac{\sqrt[n]{\prod_{j=1}^{n} C(n,j)}}{\sum_{i=1}^{n} \sqrt[n]{\prod_{j}^{n} C(i,j)}} \end{array} \right\} \tag{4}$$

Therefore, the AHP problem can be formulated as an eigenvalue problem as in equation (5) and equation (6).

$$[C]\{W_C\} = \lambda_{\max}\{W_C\} \tag{5}$$

$$|C - \lambda_{\max} I| = 0 \tag{6}$$

where [*I*] represents the identity matrix, λ_{max} denotes to the largest real positive eigenvalue of [*C*], which is equivalent to ***n***. The score vector or importance of the criteria or alternatives concerning the main one is the normalized eigenvector $\{W_C\}$. The overall flow chart of the work is presented in Fig. 2.

3. Results and discussion

To properly evaluate and compare the relative desired criteria of the natural fibers for personal body wearable bio-products made of natural fiber composites, the pairwise comparison matrices for the different model criteria were established via AHP. The judgment matrix of the model criteria with respect to the goal was also constructed as shown in Fig. 3, while Fig. 4 demonstrates the judgment matrices of the models' criteria evaluated from the intrinsic properties of fibers as well as experts feedback. It can be noticed that various different weights of alternatives with respect to each criterion have been found, where values in red color represent their reciprocals. The inconsistency value for the judgment matrix shown in Fig. 3 is 0.00 (Incon: 0.00), which acceptable according to the AHP as it is less than 0.1.The inconsistency values for each judgment matrix are also shown in the figure. This in fact demonstrates the need of multi-criteria decision making tool as human cannot easily and consistently make a direct decision regarding such conflicting criteria.

AHP was employed to compute the significance of the main criteria concerning the goal, as illustrated in Fig. 5. It can be demonstrated that the mechanical properties criterion has the highest priority in the model with about 28 %. Cellulose content comes

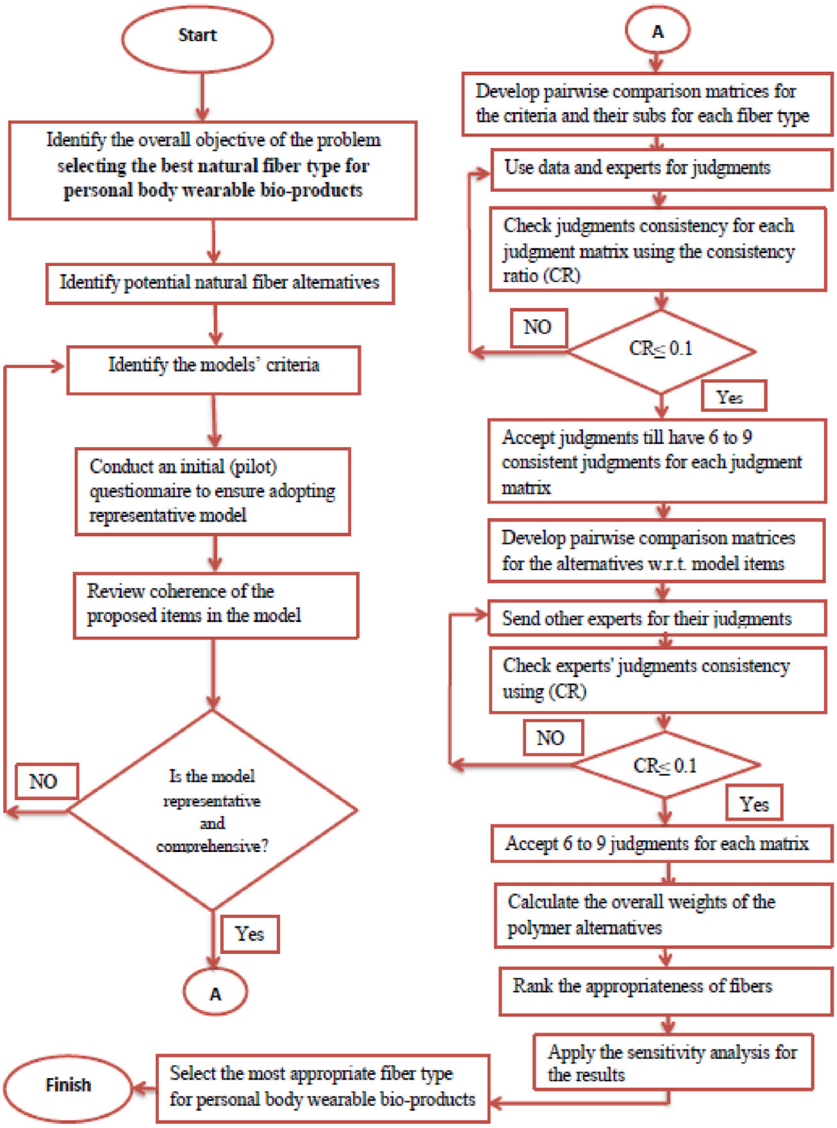

Fig. 2. The overall flow chart of the work.

	Mechanical	Comfortabi	Cost	Raw Fiber	Avaliability	Cellulose
Mechanical properties		2.5	3.01	1.5	4.25	1.0
Comfortability			1.5	(1.25)	2.5	(1.5)
Cost				(2.0)	1.5	(2.5)
Raw Fiber orientation					2.75	(1.5)
Avaliability						(4.25)
Cellulose	Incon: 0.00					

Fig. 3. The judgment matrix of the model criteria with respect to the goal.

the second with a total priority of 24.9 %. It can be noticed that none of these criteria has dominated the model with more than 50 %. This means that all considered criteria can affect the final decision of selecting the most appropriate natural fiber type for personal body wearable bio-products. Similarly, various evaluations of the alternatives with the criteria and sub-criteria in the model will be illustrated to ascertain their importance on the alternatives based on AHP.

Going deep in the mechanical properties criterion, Fig. 6 demonstrates the relative priorities of the considered available alternatives regarding the mechanical properties sub-criteria: tensile strength, and Young's modulus. It can be illustrated that hemp fiber

Cellulose

	Cocos nuci	Cotton	Hemp	Bannana	Ramie	Sugar palm
Cocos nucifera sheath		3.73	3.35	2.68	3.09	1.67
Cotton			(1.11)	(1.38)	(1.2)	(2.22)
Hemp				(1.24)	(1.08)	(2.0)
Bannana					1.15	(1.6)
Ramie						(1.86)
Sugar palm	Incon: 0.00					

Cost

	Cocos nuci	Cotton	Hemp	Bannana	Ramie	Sugar palm
Cocos nucifera sheath		9.92	6.48	1.77	15.9	5.3
Cotton			(1.5)	(5.63)	1.6	(1.87)
Hemp				(3.75)	2.4	(1.25)
Bannana					8.95	3.01
Ramie						(3.01)
Sugar palm	Incon: 0.00					

Comfortability \ Size

	Cocos nuci	Cotton	Hemp	Bannana	Ramie	Sugar palm
Cocos nucifera sheath		(2.34)	(1.13)	(1.04)	(1.16)	1.02
Cotton			1.03	1.12	1.02	1.2
Hemp				1.01	(1.02)	(1.16)
Bannana					1.1	(1.08)
Ramie						(1.18)
Sugar palm	Incon: 0.01					

Avaliability

	Cocos nuci	Cotton	Hemp	Bannana	Ramie	Sugar palm
Cocos nucifera sheath		2.91	2.56	2.41	3.15	4.1
Cotton			(1.14)	(1.21)	1.07	1.4
Hemp				(1.06)	1.23	1.6
Bannana					1.3	1.7
Ramie						1.3
Sugar palm	Incon: 0.00					

Comfortability \ Wei

	Cocos nuci	Cotton	Hemp	Bannana	Ramie	Sugar palm
Cocos nucifera sheath		2.3	1.13	1.04	1.15	(1.02)
Cotton			(1.03)	(1.12)	(1.02)	(1.2)
Hemp				(1.09)	1.02	(1.16)
Bannana					1.1	(1.07)
Ramie						(1.18)
Sugar palm	Incon: 0.01					

Fiber orientatio

	Cocos nuci	Cotton	Hemp	Bannana	Ramie	Sugar palm
Cocos nucifera sheath		5.49	2.1	2.8	1.4	3.3
Cotton			(2.6)	(1.95)	(4.0)	(1.5)
Hemp				1.4	(1.5)	1.6
Bannana					(2.0)	1.15
Ramie						2.4
Sugar palm	Incon: 0.00					

Fig. 4. Judgment matrices of the considered model criteria with the alternatives.

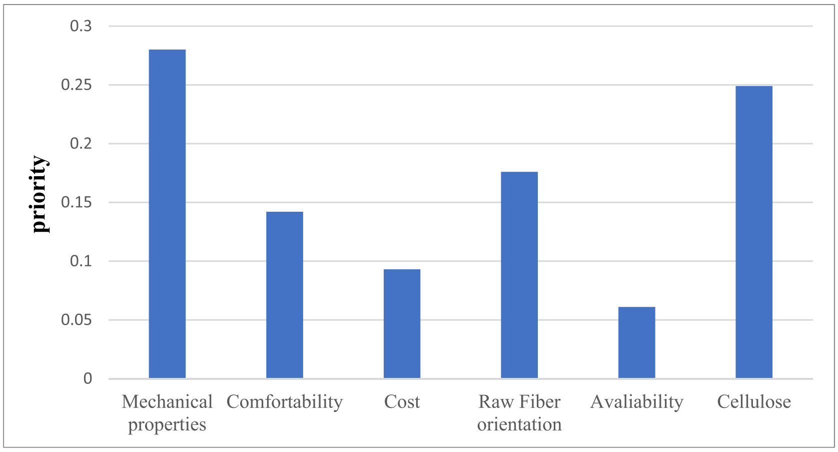

Fig. 5. Total priority of the considered criteria in the model with respect to the goal.

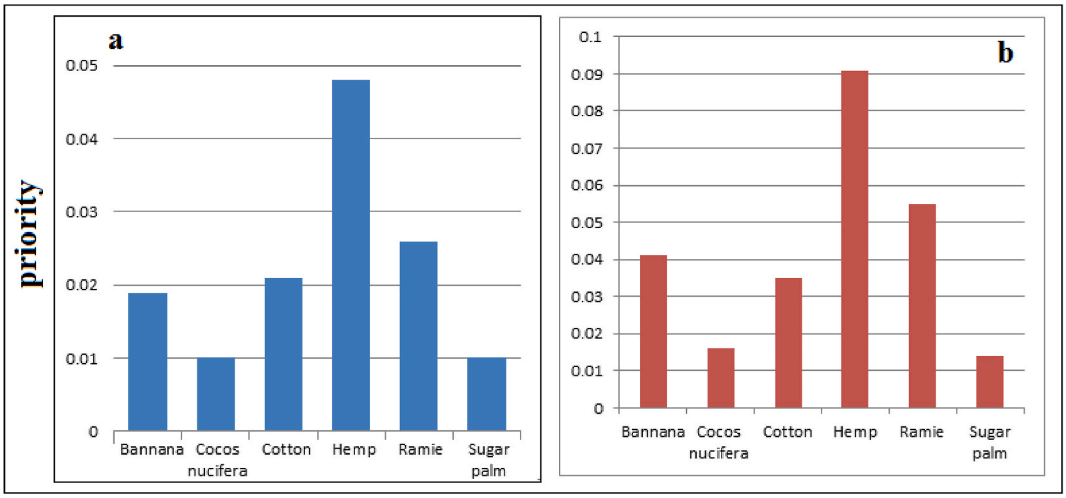

Fig. 6. The priorities of the considered natural fibers regarding mechanical properties a) tensile strength, and b) Young's modulus.

has the highest value priority of this criterion with about 4.8 %, while ramie fiber has the second higher priority with 2.6 % of tensile strength sub-criterion as seen in Fig. 6a. On the other hand, the relative importance of the alternatives regarding the Young's modulus criterion is shown in Fig. 6b. It demonstrates that both hemp and ramie fiber types have the best priorities with values of 9.1 % and 5.5 % respectively. However, the fiber with the third priority was banana with 4.1 %, while the third priority regarding the tensile strength was cotton fiber type. This demonstrates the fact that various natural fibers have different characteristics regarding different evaluation criteria; the matter emphasizes deeper evaluations of the natural fiber capabilities for a particular application.

On the other hand, Fig. 7 illustrates the total priorities of the considered natural fibers regarding both the mechanical properties and the raw fiber orientation main criteria in the model. Results have revealed that all of hemp, ramie and banana according to Fig. 7a are the best fiber alternatives regarding the mechanical properties main criterion with a priority of 4.3 %, 2.9 % and 2.2 % respectively. The closeness of the priorities between the coconut sheath and sugar palm makes it difficult to judge which fiber is better regarding the mechanical properties without using such MCDM tool.

The priority of the alternative fibers regarding the raw fiber orientation demonstrates that the best alternatives regarding this property are cocos nucifera (coconut sheath) and ramie fibers with priorities of 5.7 % and 4.1 % respectively according to Fig. 7b. However, hemp came third with priority of 2.8 %. Moreover, the priories with respect to comfortability as well as cost main criterion in the model are illustrated in Fig. 8. It can be seen that coconut sheath and banana according to Fig. 8a are the best regarding the cost main criterion. However, the priority of the comfortability is different as shown in Fig. 8b. The best fibers regrading comfortability criterion are found to be sugar palm, coconut sheath and banana. In addition, the priorities of the natural fibers regarding the cellulose content main criterion and availability are illustrated in Fig. 9. It can be found here that both coconut sheath and sugar palm are the best regarding cellulose content main criterion in the model according to Fig. 9a. However, the best fiber type regarding availability was found to be the coconut sheath, and both banana and hemp fiber types were ranked second with equal priority of 0.8 % as shown in

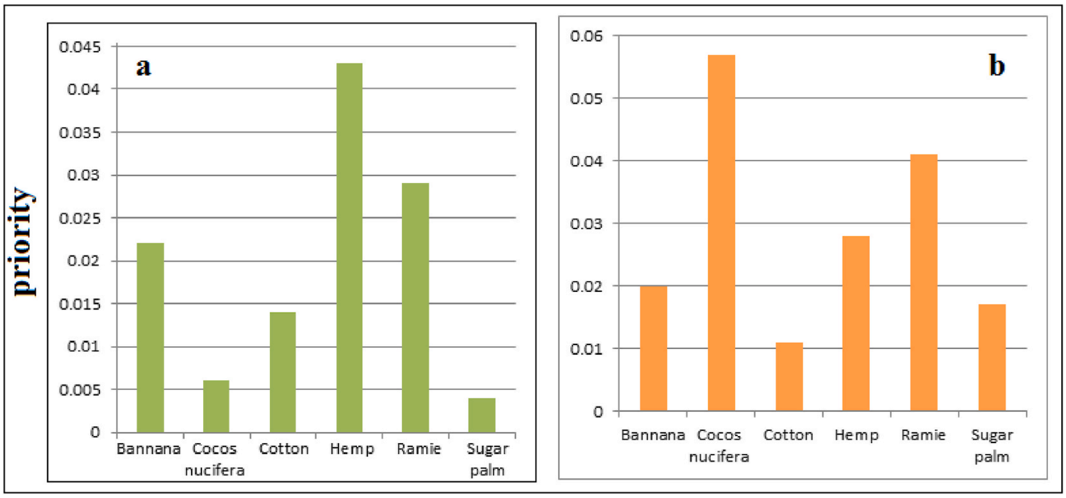

Fig. 7. The priorities of the considered natural fibers regarding a) the mechanical properties main criterion, and b) the raw fiber orientation main criterion in the model.

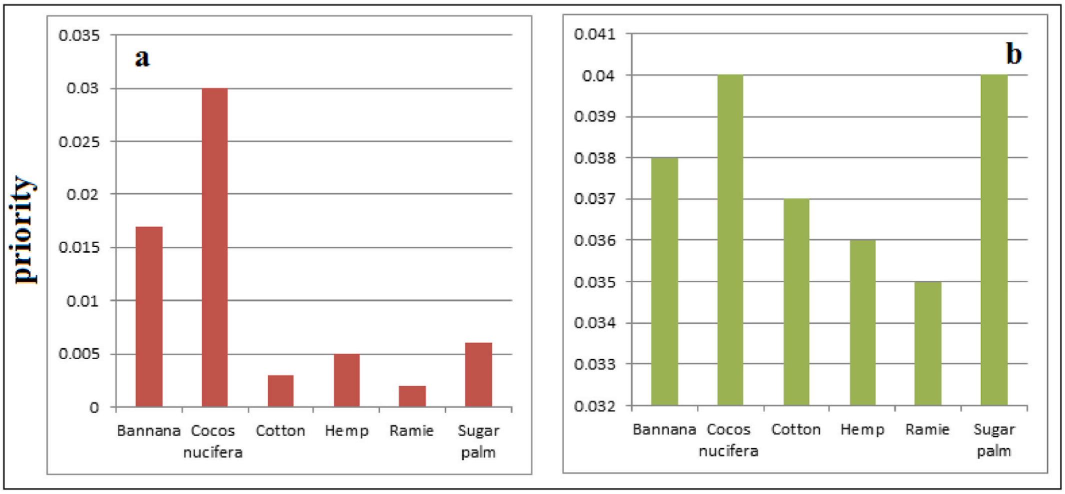

Fig. 8. The priorities of the considered natural fibers regarding a) cost main criterion, and b) comfortability.

Fig. 9b.

Moreover, the AHP was employed to calculate the significance of the natural fiber alternatives with each main criterion in the model as demonstrated in Fig. 10. It can be shown that hemp fiber has the highest priority regarding the mechanical properties main criterion in the model with a value of 9.1 %. However, coconut sheath has the higher priority regarding the cellulose content criterion with a value of 8.1 % and raw fiber orientations criterion with a value of 5.7 %. It can also be noted that all alternatives have almost similar priorities for the comfortability and other criteria.

The closeness of priorities of the various fibers with respect to different considered criteria in the model makes the decision a matter of multi-criteria decision making problem. This would make a misleading in the selection process of the best natural fiber for personal body wearable bio-products. Consequently, simultaneous assessment of the considered fibers regarding the overall considered criteria in the model has to be conducted. This has been revealed and demonstrated in Fig. 11. It can be demonstrated that the coconut sheath was the best regarding the whole considered criteria with a priority of 24.5 %. The second best fiber was hemp with an overall priority of 19.1 %. Ramie on the other hand, was the third best alternative with a priority of 16.6 % followed by banana, sugar palm and cotton with priorities of 15.4 %, 13.0 % and 11.4 % respectively. For more details, the priorities of the considered fiber alternatives regarding

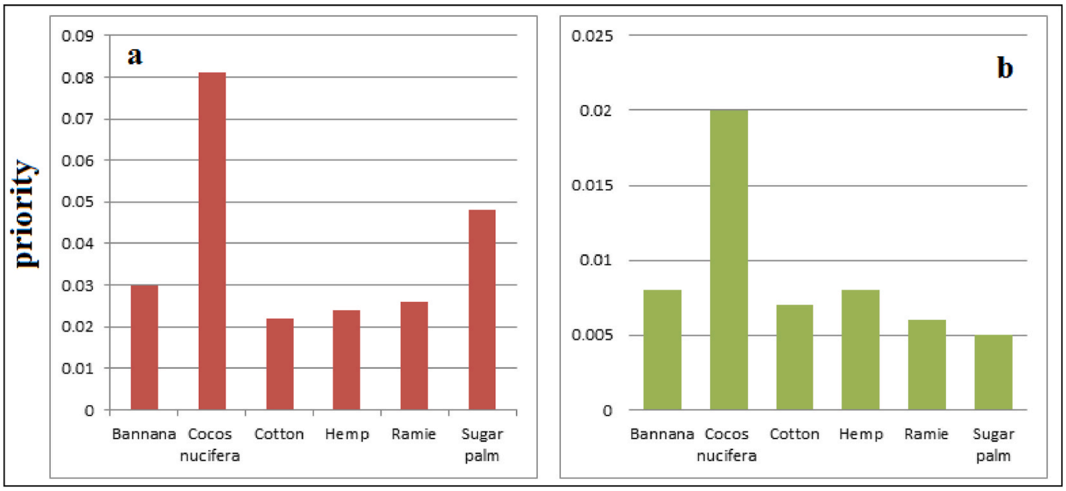

Fig. 9. The priorities of the considered natural fibers regarding a) cellulose content main criterion, and b) availability.

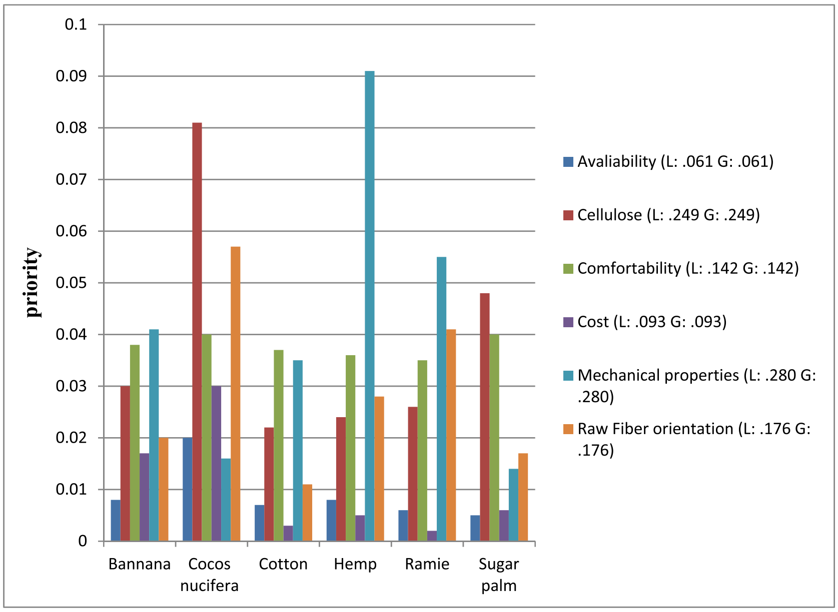

Fig. 10. The significance of the natural fiber alternatives with each main criterion in the model.

comfortability main criterion and its sub-criteria are tabulated in Table 5 and Table 6.

The sensitivity analysis of the considered model was carried out to demonstrate the robustness of the gained results and to clarify the impact of altering various parameters of the model on the selection of the best fiber alternative for the personal body wearable bio-products. Utilizing the current values of main criteria weights are demonstrated in Fig. 12. It is showing the rank of the alternatives on the left. However, altering the weights of the main criteria by making one factor dominant in the model (having a weight more than 50 %) like that of cellulose content criterion as shown in Fig. 13 did not changed the best alternatives in the model. This means that the gained result ranking is robust and did not dramatically influence by the sudden change of the weights. So, the dynamic response of the model is consistent.

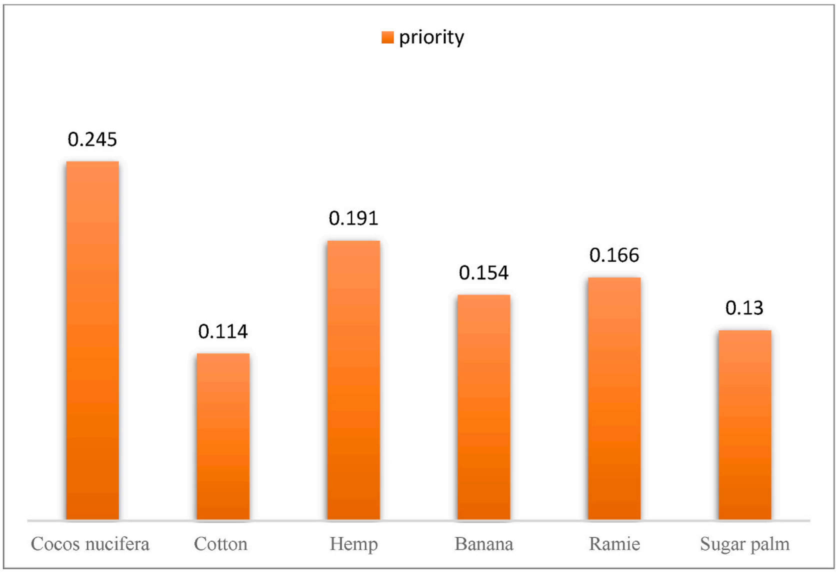

Fig. 11. Overall priority of the model.

Table 5
Priority of alternatives with respect to comfortability main criterion and its weight sub-criteria.

Main criteria	Sub-criteria	Alts	Priority
Comfortability	**Weight**	**Cocos nucifera**	**0.029**
Comfortability	**Weight**	**Cotton**	**0.02**
Comfortability	**Weight**	**Hemp**	**0.023**
Comfortability	**Weight**	**Banana**	**0.025**
Comfortability	**Weight**	**Ramie**	**0.022**
Comfortability	**Weight**	**Sugar palm**	**0.026**

Table 6
Priority of alternatives with respect to comfortability main criterion and its size sub-criteria.

Main criteria	Sub-criteria	Alts	Priority
Comfortability	**Size**	**Cocos nucifera**	**0.011**
Comfortability	**Size**	**Cotton**	**0.017**
Comfortability	**Size**	**Hemp**	**0.013**
Comfortability	**Size**	**Banana**	**0.013**
Comfortability	**Size**	**Ramie**	**0.013**
Comfortability	**Size**	**Sugar palm**	**0.014**

Moreover, altering the weights of the model's criteria by reducing the weight of mechanical properties and cellulose content as well as increasing the weight of availability and cost to be all with almost similar weights would alter the considered fibers for the main goal of the study. That can be shown in Fig. 14. It can be noticed that the ranks of the best alternatives have not been changed too, and still being the coconut sheath and hemp fibers. This demonstrates the robustness in selecting these fibers for the goal of the study.

4. Conclusions

Mathematical representation of the AHP formulation and structure were capable of building a model to evaluate and properly select the most appropriate natural fiber types for bio-composite material suitable for personal body wearable bio-products. This would contribute to developing the sustainability of intelligent green wearable devices as it would advance the selection process of natural fiber reinforced composite materials suitable for personal body wearable bio-products. The model was capable of dealing with several conflicting criteria to evaluate the relative merits of natural fibers considering their various intrinsic characteristics. Although the model has limited types of natural fibers and technical evaluation criteria, its novelty in the field of intelligent wearable devices made from bio-composites would help selecting available natural waste materials for the advance of industrial sustainability that align with the sustainability goals and promote cleaner production practices. It was found that the mechanical properties criterion had the highest priority in the model with about 28 %. Cellulose content was also found significant with a total priority of 24.9 %. Moreover, all the

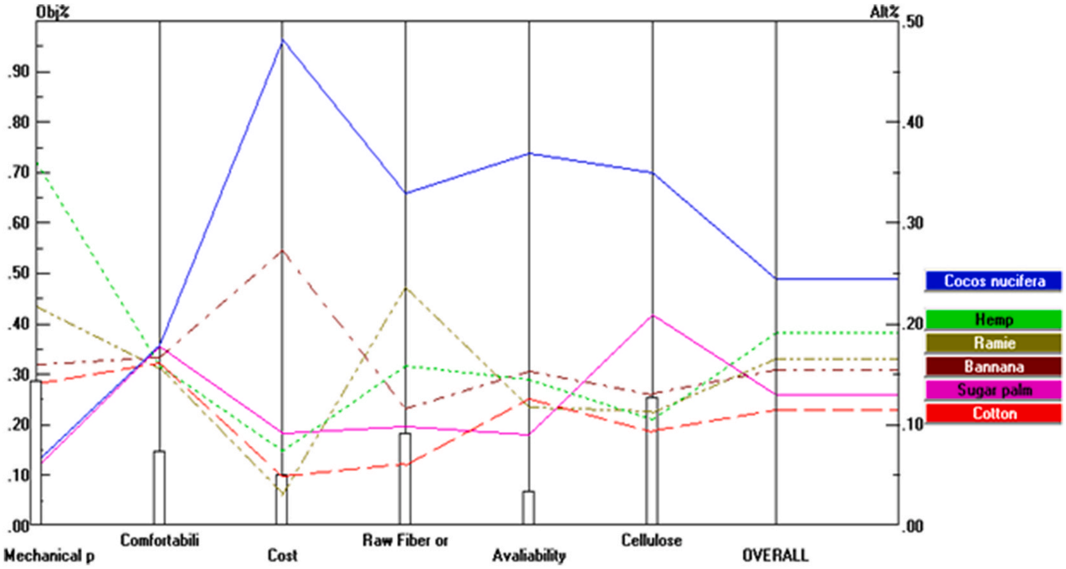

Fig. 12. Current values of main criteria weights.

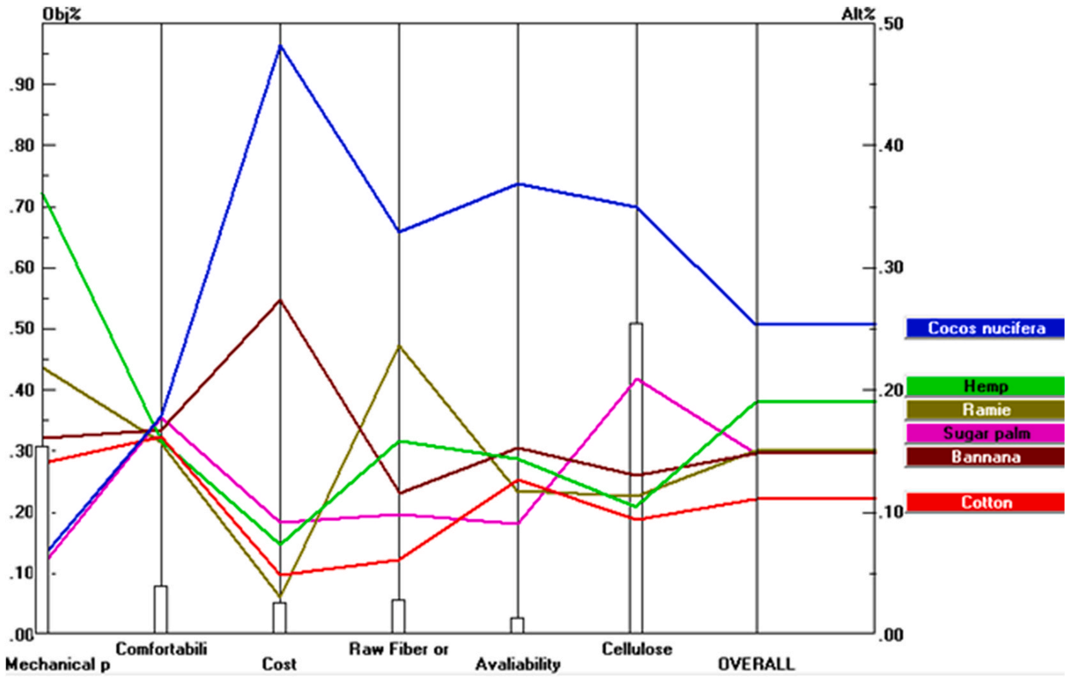

Fig. 13. Dynamic response of sensitivity analysis for a dominant factor case.

evaluation criteria were found effective in the evaluation as no dominant factor was found in the model. Hemp fiber type was found to have the highest value priority regarding the tensile strength and Young's modulus mechanical properties. However, it was not the best selected fiber in the model. Ramie fiber had the second higher priority of 2.6 % regarding tensile strength sub-criterion, while cotton fiber type was not found potential among the considered fiber types regarding this particular property. In addition, coconut sheath and ramie fiber types exhibited potential characteristics to be ranked as the best regarding the cost main criterion. However, the priority of the comfortability was different as sugar palm, coconut sheath and banana were found the best. On the other hand, coconut sheath

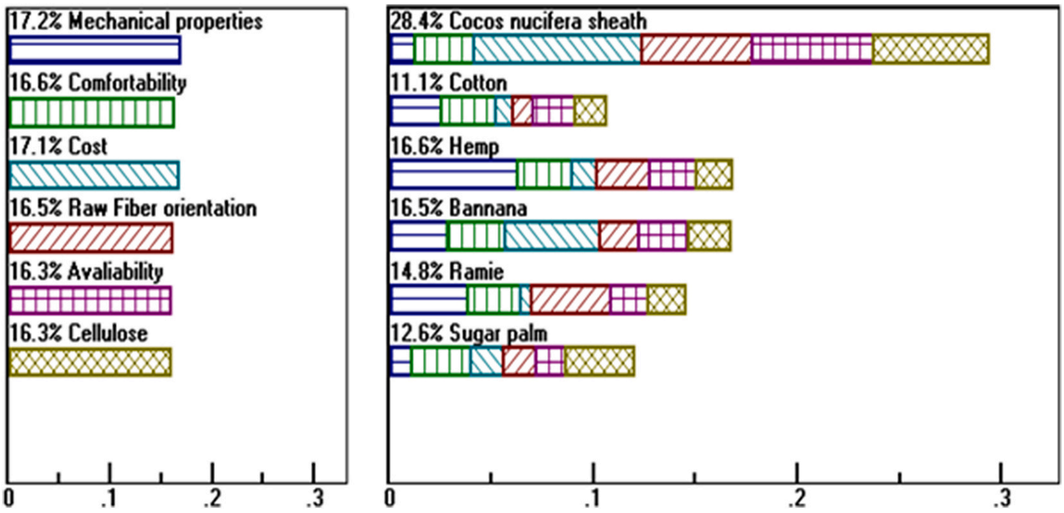

Fig. 14. Sensitivity analysis with equal weight case.

fiber type had integrated potential characteristics to be the best regarding the whole considered criteria in the model. The sensitivity analysis demonstrated the robustness of the gained results of the model. Both dominant factor and equal weight sensitivity types showed that the best alternatives were not altered with dramatically changing the weights of the evaluation criteria in the model. This in order would enhance the proper evaluations of the natural fiber alternatives for bio-composite materials suitable for personal body wearable bio-products, which would improve the reliability of the selection process and avoiding bias in the decision making problem for the designers to enhance more sustainable design possibilities in this field.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

The authors confirm that the data supporting the findings of this study are available within the article.

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CRediT authorship contribution statement

Faris M. AL-Oqla: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Mohammed T. Hayajneh:** Software, Resources, Data curation. **Y.A. El-Shekeil:** Writing – original draft, Validation, Resources, Data curation, Conceptualization. **H.A. Refaey:** Writing – original draft, Software, Data curation, Conceptualization. **Samir Bendoukha:** Writing – original draft, Resources, Data curation, Conceptualization. **Nabil Barhoumi:** Writing – original draft, Resources, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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