Application of Shannon's Entropy-Analytic Hierarchy Process (AHP) for the Selection of the Most Suitable Starch as Matrix in Green Biocomposites for Takeout Food Packaging Design

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Starch is a natural polymer and eligible for short-term, single-use food packaging applications. Nevertheless, different starches have different features and properties determined by their botanical plant origins. This paper presents an approach that combines Shannon's entropy and the Analytic Hierarchy Process method to aid the selection process of starch as matrix in green biocomposites for takeout food packaging design. The proposed selection system ranks alternative starches in terms of the key design elements, *i.e.* strength, barrier property, weight, and cost. Shannon's entropy established corresponding weight values for the indicators selected. Six starches: wheat, maize, potato, cassava, sago, and rice were appraised using gathered data from the literature to determine their suitability as a more sustainable option. This study found that sago starch obtained the highest priority score of 26.8%, followed by rice starch (20.2%). Sensitivity analysis was then carried out to further verify the results; sago starch was at the top rank for five of six different scenarios tested. The results showed that sago starch is the starch that can best satisfy the design requirements. Despite the results attained, the selection framework used could be enhanced with a more comprehensive attributes assessment and extensive dataset.

Keywords: Material selection; Food packaging; Starch; Biopolymer; Shannon's entropy; AHP

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INTRODUCTION

Starch-based plastics are prominent amongst bio-based materials. They had a global production of 668,000 tons in 2013, and the estimated growth from 2013 to 2020 was 94.3%, with a production rate of 1,298,000 tons per annum (Ortega-Toro *et al.* 2017). Starch is an organic glucose-based polymer and has a high potential for usage in biodegradable and environmentally compatible materials with many advantages, such as relatively low cost, abundance, high purity, and renewability (Fabra *et al.* 2016b; Samsudin and Hani 2017). Starch is obtained from a variety of plant tissues, in the form of granules. It is a polysaccharide, comprised of D-glucose units, either homoglucan or glucopyranose. When starch is mixed with a plasticizer at high temperatures (90 °C to 180 °C) and sheared, it melts and becomes fluidized, thus allowing the usage of similar equipment for synthetic plastic manipulations such as injections, extrusions, and blowing (Sumathi Leema *et al.*

2016; Ortega-Toro *et al.* 2017).

The rapid increase in interest of biocomposites material in the past decades can be attributed to environmental motivations and governmental regulations. Waste management related issues are primarily caused by non-biodegradable plastic wastes, mostly from single use and short lifespan food packaging. Thus, bio-degradable and compostable materials, which are derived from renewable resources, such as starch, would be the best alternative. Various studies that have been done on the development of starch-based materials demonstrate their suitability for a specific packaging application. The final properties of starch-based composites materials can be influenced by many factors, with emphasis placed on the type of starch used, the chemical modifications performed, and the processing conditions. When starch is used alone, it forms a very weak material. However, its properties could be enhanced by reinforcing it with natural fibers, which are also bio-based and renewable. Creation of reliable natural fiber reinforced starch-based composites materials, with the appropriate properties suitable for food packaging applications would allow for the replacement of non-degradable conventional plastics.

Materials selection is a crucial process and is the foundation of any engineering applications or product design. In composite product design and development, a concurrent engineering (CE) environment helps the material designers to develop the design requirements with the input from various stakeholders to ensure the design objective is fulfilled (Sapuan and Mansor 2014). This includes the selection of a natural fiber and biopolymer matrix to form innovative green biocomposites materials. Selecting the right constituent materials when designing biocomposites materials is not an easy task and is a critical aspect in the CE approach. The appropriate selection of materials becomes a vital part of the process in order to achieve successful sustainable designs, while satisfying key features for customer satisfaction. For materials to be utilized for food packaging applications, they must be able to fulfil the functional requirement of the product, as well as the common fundamental functions of food packaging; containment, protection, preservation, and convenience (Verghese *et al.* 2012; Piergiovanni and Limbo 2016). However, the utilization of thermoplastic starch as a matrix for biocomposite materials is often restricted by several constrains and factors. Picking the right biopolymer for an application is a complex matter where thorough decisions are necessary. If thermoplastic starch were to be utilized as a matrix for green biocomposites synthesis, selecting the most appropriate type of starch would be a challenging task.

An abundance of studies on the material selection process under the topic of composite product development and design have been done in the recent past. Among the most recent studies are Al-Oqla and Salit (2017), Mastura *et al.* (2017), and Mastura *et al.* (2018). However, these studies focused on materials selection for automotive parts design. It is worthy to mention here the work of Sanyang and Sapuan (2015) on the selection of a bio-based polymer for specific packaging (packed fruits, dry food, and dairy products). They proposed a selection process developed through the usage of an expert system using Exsys Corvid software, by applying a “If – Then” rule-based system. The system first screened materials that satisfied all determined criteria, *i.e.*, the gas and water vapor barrier and the mechanical properties. The results found polylactic acid (PLA) as the most suitable material for the packaging of packed fruits, dry food, and dairy products. Another study, by Almeida *et al.* (2017), was on the selection of materials for food packaging design, to be exact, a refillable water bottle, where the authors exploited environmental accounting based on an energy accounting approach. Almeida *et al.* (2017) assessed information on the environmental cost for each alternative material to pick the most suitable one for the application. However, the materials evaluated were limited to the resources available in Brazil, *i.e.*, glass, polyethylene terephthalate (PET), and aluminum.

The analytic hierarchy process (AHP) method is a powerful decision-making technique that allows both tangible and non-tangible characteristics to be considered to attain the desired priorities and make the most appropriate decision. This approach has been utilized in many material selections studies. It has assisted materials designers and engineers in determining the most suitable composite materials and/or constituent materials for application in a variety of engineering components. The most useful feature of AHP analysis is the balanced interpretation of the problem that is gained from the multiple criteria input, where it gives an overview of the problem in totality by incorporating all the appropriate criteria (Khaira and Dwivedi 2018). Among the numerous studies applying AHP for the selection of composite materials for specific design applications is Hambali *et al.* (2010). They utilized AHP in the selection framework to find the most suitable composite materials for an automotive bumper beam by assessing eight main selection factors and 12 sub-factors onto six alternatives. On the other hand, Sapuan *et al.* (2011) applied the AHP to evaluate 29 natural fibre reinforced composites (NFRC) alternatives to select the most appropriate NFRC for a dashboard panel design. Sapuan *et al.* (2011) considered two main factors, the mechanical and physical properties of the NFRC candidates. Additionally, Mansor *et al.* (2013) used the AHP method to determine the most suitable natural fibre to be hybridized with a glass fibre to reinforce polymer composites for the design of a center lever parking brake. Mansor *et al.* (2013) assessed 13 natural fibre candidates for the hybridization process based on the ability of their characteristics and properties to fulfil the three main performance categories according to the product design specifications (PDS). It is also important to note that the study by Al-Oqla *et al.* (2016), used AHP to develop a decision-making model to appraise and determine the most appropriate composites for the design of interior parts of a vehicle. The six evaluation criteria for the composites were their tensile strength, tensile modulus, flexural strength, flexural modulus, impact strength, and the maximum water absorption. Briefly, in composites related selection studies, AHP were utilized either to find a natural fiber as reinforcement in composites, or selection of a polymer matrix for a specific product design.

From the literature and to the best of the authors' knowledge, this study is the first to investigate a selection system of the most appropriate starch as matrix in green biocomposites for the application of takeout food packaging design. The selection system proposed is a combination of Shannon's entropy and AHP through the usage of Experts Choice software in generating the priority ranking scores. This study also utilized the opinions of biocomposite experts on the importance of the various attributes of starch for the selection to achieve the intended performance standards of takeout food packaging designs. The proposed selection system would aid food packaging designers and decision makers on reaching the top choice of starch according to the packaging design criteria and constraints. This model could also be a point of reference for decision makers in evaluating and selecting further types of starch to achieve more sustainable design possibilities.

EXPERIMENTAL

The overall work done in this paper is diagrammed in Fig. 1. Shannon's entropy methodology was employed to determine the weight values of the criteria for each starch, and then the AHP-based Experts Choice software (11.5 , Expert Choice Inc, Arlington, VA) was applied *via* pairwise comparisons of the starch attributes, in order to derive a priority ranking of the starch alternatives.

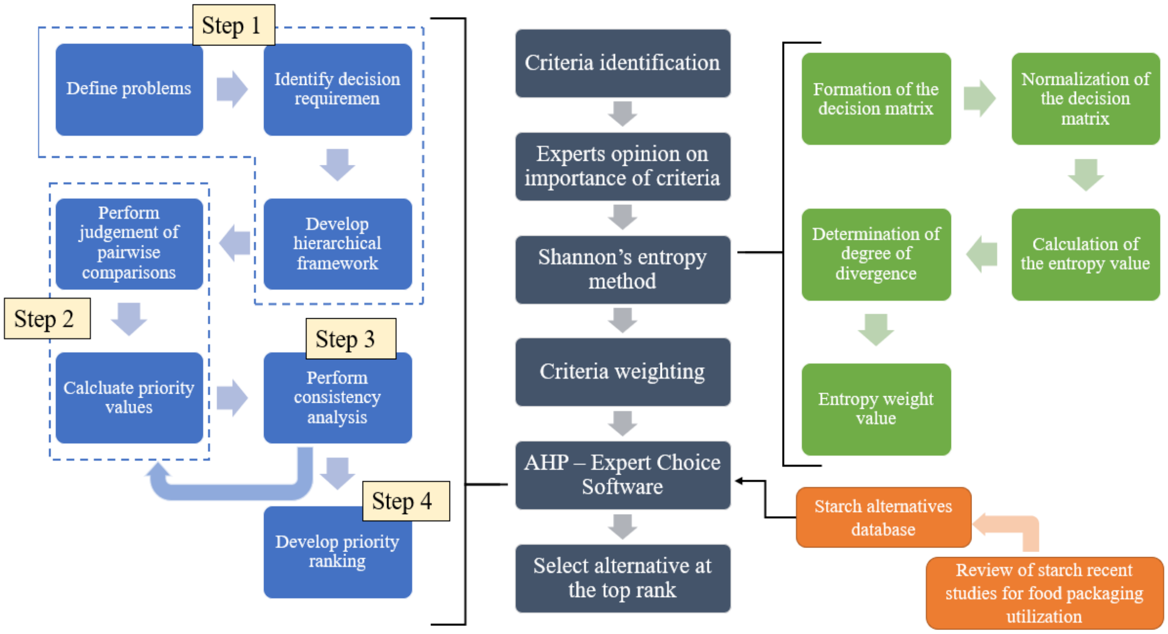


Fig. 1. Workflow of this study

Criteria Identification

A critical aspect in developing an innovative starch-based material for a specific application is the selection of the right starch. Choosing the right starch for the design of a starch-based material for a specific application would be a challenging task. Therefore, the first step in this study was to determine the characteristics of the starch alternatives that had the potential to be utilized for food packaging design. Each type of starch has different characteristics and properties, according to their botanical plant origins. Important criteria for the selection process of starch-based materials can be determined according to the properties of the starches, which are comprised of the unique attributes and characteristics for each type of starch. Numerous factors must be considered in the process of selecting the right starch to fulfil the design and manufacturing requirements (Al-Oqla and Salit 2017; Rezkazemai *et al.* 2018). For food packaging, the design requirements need a complex process for the determination of the criterion, due to the active nature of food products (Sanyang and Sapuan 2015). Criteria that could affect the starch selection process are shown in Table 1, which could be used as a model for the industry to enhance the selection process of the most appropriate starches for a given application. In addition, according to Russo and Camanho (2015), as the AHP analysis makes decisions that involve the selection of possible alternatives, it would be acceptable for the selection criteria to be defined based on these alternatives.

Food packaging is meant to inhibit the gain or loss of moisture, prevent microbial contamination, and act as a barrier against the permeation of water vapor, oxygen, carbon dioxide, and other volatile compounds, such as flavours and stains (Rhim *et al.* 2013). Appropriate packaging should also ensure the proper safety and quality of food products all the way from the processing and manufacturing stage through handling, storage, and finally consumption of the protected food product (Sanyang *et al.* 2016). Currently applied bio-based products are reported facing critical challenges to penetrate the market. Two of the three main obstacles are cost related issues: (1) the material cost, and (2) the manufacturing cost (and time). Another major constraint is the sustainability of obtaining the raw material, and its recyclability (Garofalo *et al.* 2018).

The aspects of the packaging requirements and costs discussed above were the basis for developing the selection criteria to determine the most appropriate starch to be utilized for takeout food packaging materials. Chemical properties of the starch reflect their mechanical properties, and there are many other factors that may affect their properties and could be incorporated in the selection system. However, the selection criteria established in this study was reduced due to limitations in the accessibility and availability of data on starches according to their botanical sources. Only nine attributes of starch were chosen for this selection system. These criteria were clustered according to both the general requirements of the materials for food packaging application and the aspect of design and manufacturing. “Strength” and “barrier property” were determined as among the main criteria to fulfil the materials requirement where physical and chemical properties of starch would be assessed.

Table 1. Anticipated Criteria Influencing the Selection of a Thermoplastic-starch for a Specific Application

Physical	Chemical / Biological	Mechanical	Technical	Environmental
• Granule diameter • Particle structure • Crystalline structure/ Crystallinity • Texture • Gas / Water Permeability • Density • Thermal characteristics • Specific heat • Opacity • Surface image	• Chemical composition* • Batch quality • Consistency of batch quality • Availability • Resource shortage • Planting limitations • Burning rate	• Tensile strength • Elongation at break • Young's modulus • Yield strength • Specific yield strength • Poisson's ratio	• Type and amount of plasticizer/ • Processing knowledge and time • Raw cost • Transferring cost • Processing conditions • Processing energy consumption • Cost of energy input (cellulose extraction, machine *etc.*)	• Biodegradability • Eco-friendly • Government support • Social positive view
*(Amylose, amylopectin, protein content, lipid content, water content, and ash)				
adapted from Al-Oqla *et al.* (2015)				

Weight is a crucial factor in food packaging products for convenience on the filling and packaging line and in distribution (Emblem and Emblem 2012). Cost is another important aspect of product development, and production is the most essential factor affecting company’s cost (Ehrlenspiel *et al.* 2007). The selection criteria for the proposed selection framework are described in Table 2.

Table 2. Selection Criteria Chosen for the Making Decision Process for the Most Suitable Starch for Takeout Food Packaging Design

Primary Criteria	Starch Properties	Unit	Description
Strength	Amylose	%	Contributes to the mechanical behavior, a higher amount will give greater strength and toughness to the material
	Amylopectin	%	A lower amylopectin content in a native starch means a higher degree of crystallinity
	Protein Content	%	Lower protein content means higher starch content
	Granule Diameter	µm	Smaller granules would produce larger surface area to volume ratio and hence greater strength of inter-particulate bonding (cohesion)
Barrier properties	Moisture Content	%	Determine the crystallinity and barrier properties
	Ash	%	A lower ash content indicates a cleaner content of starch, and so lower porosity and water permeability
Weight	Density	(g/m^3)	To identify lighter thermoplastic starch-based material
Cost	Raw cost	-	To determine the price of the material
	Availability	-	To measure the transportation needs to supply the natural fibre from its origin location

Adapted from (Bogracheva *et al.* 2002; Eichie and Kudehinbu 2009; Gunorubon and Kekpugile 2012; Al-Oqla *et al.* 2015; Woggum *et al.* 2015; Jumaidin *et al.* 2016; W. Yu *et al.* 2016; Lorente-Ayza *et al.*; 2016 Khan *et al.* 2017; Mastura *et al.* 2017; Ortega-Toro *et al.* 2017; and Sanyang *et al.* 2018)

Utilization of AHP-based Expert Choice Software

Further development of the selection framework was performed *via* the AHP using Expert Choice software. The primary steps for the utilization of AHP include: (1) define the problem; (2) develop a hierarchy structure model to find the most suitable starch for food packaging; and (3) construction of a pairwise comparison matrix. A four-level hierarchy structure was developed, with the goal of study at the top of the structure (as shown). The nine starch's attributes selected (as shown in Table 2) were grouped based on the design requirement, and they were the components for the second level of the hierarchy, *i.e.*, the primary criteria in the selection process. For the third level, there were four sub-criteria for the strength category, two sub-criteria for the barrier property category, one sub-criterion for the weight category, and two sub-criteria for the cost category. The lowest level was composed of the starch alternatives. The proposed AHP hierarchy structure is shown in Fig. 2. This hierarchy structure was constructed in Expert Choice software and automatically the pairwise comparison judgement matrix was constructed.

The judgement process began with a pairwise comparison of the primary criteria with respect to the overall goal, *i.e.*, the selection of the most suitable starch for food packaging application. A comparison judgement was performed to determine the relative importance of each pair for the four primary criteria.

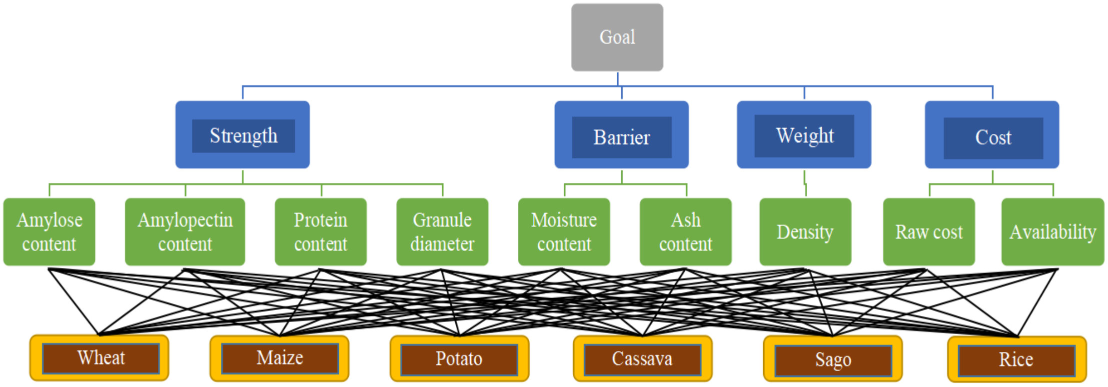
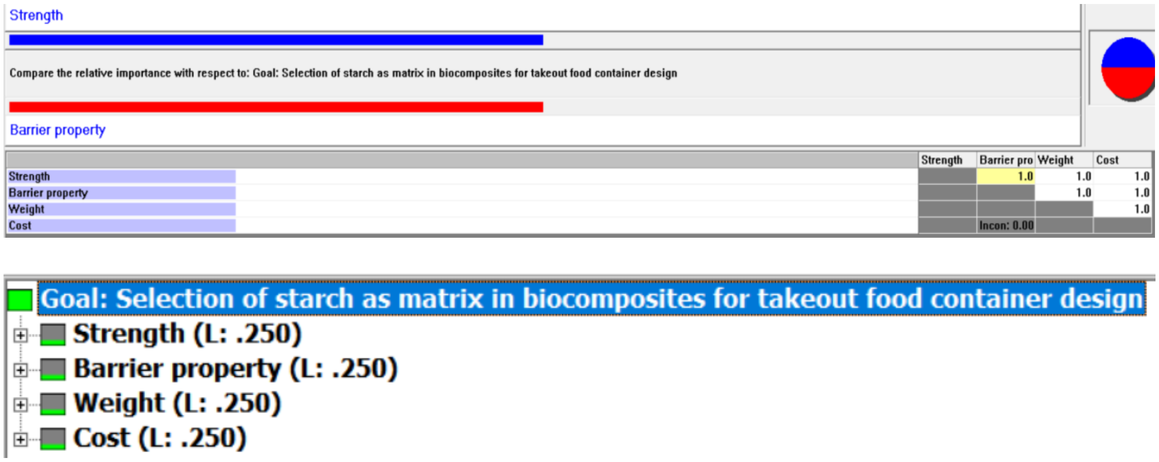


Fig. 2. Proposed hierarchy structure with respect to goal of study

The assigned value for each pairwise comparison was 1.0, which indicated that they held equal important. The pairwise matrix for the primary criteria, with respects to the overall goal and the weight values assigned to the primary criteria are shown in Fig. 3. The strength, barrier property, weight and cost primary criteria contributed an equal priority vector. The priority vectors and the consistency ratio were examined after the pairwise comparison judgement was performed and the consistency ratio value (CR = 0.00) was less than 0.1; therefore, the pairwise comparison judgement was acceptable. If the consistency ratio was greater than 0.1, the judgment matrix would be inconsistent, and the judgement would have to be reviewed and improved in order to obtain a consistent matrix.


Strength

Compare the relative importance with respect to: Goal: Selection of starch as matrix in biocomposites for takeout food container design

Barrier property

	Strength	Barrier pro	Weight	Cost
Strength		1.0	1.0	1.0
Barrier property			1.0	1.0
Weight				1.0
Cost		Incon: 0.00		

Goal: Selection of starch as matrix in biocomposites for takeout food container design
- Strength (L: .250)
- Barrier property (L: .250)
- Weight (L: .250)
- Cost (L: .250)

Fig. 3. The pairwise comparison matrix for the primary criteria, with respects to the overall goal and the weight values appointed to the primary criteria

Criteria Weighing and Database Development for the Attributes of the Alternative Starches

In the decision-making process to select the most appropriate material, deciding on the relevant attributes or decision factors is one of the key elements. In addition, evaluating the importance of each criterion can differ for each one (Mousavi-Nasab and Sotoudeh-Anvari 2017). Therefore, determining the appropriate weights for each criterion was vital for the decision-making framework. The opinions of the experts and/or decision makers are vital in assigning a weight value to each criterion and will affect the results value. It is important to note that specifying a weight value to the identified criteria must be carefully done in order to prevent bias. Evaluations of the criteria were gathered *via* an electronic survey questionnaire sent to local and external experts in the fields of biopolymer and biocomposites. The experts' criteria are summarized in Table 3.

Table 3. Experts' Criteria Established

Researchers/ Academician	Industry
• Ph.D. holder; AND at least three years of experience in relevant biocomposites area of study; AND have published at least three papers in relevant biocomposites • Master's degree holder; AND at least three years of experience in thermoplastic starch/ biopolymer; AND at least have published three papers relevant biopolymer	• At least holding a bachelor's degree in materials science/ engineering; AND at least five years of experience in biopolymer materials

Fifteen (15) experts who fulfilled the requirements participated in the survey. The experts were asked to rate the level of importance of each criterion using a scale of 1 to 7, where a 1 represented "not at all important" and a 7 represented "extremely important" (Vagias 2006). The responses from experts were recorded and affixed in the Appendix I.

The subjective weights were determined according to the preference of experts in the survey. However, obtaining reliable subjective weight values was difficult; therefore, the use of objective weight values would be beneficial. The objective weight value measurement proposed was Shannon's entropy which is similar used in Zhang (2015)'s, Haddadha *et al.* (2017), He *et al.* (2018) and Ishak *et al.* (2017). The entropy method determines the weight values by solving mathematical models without the consideration of the preferences of the decision makers. The concept of Shannon's entropy is meaningful in information theory and is now applied as a reference to a general measurement of uncertainty. In a multi-attribute decision-making method (MADM), a greater entropy value for a specified attribute corresponds to a lower weight value for that attribute. In addition, this corresponds to a lesser amount of discriminatory power that the attribute has in the decision-making process (Lotfi and Fallahnejad 2010).

Entropy derived weights are represented as 1 minus the entropy value and the structure of the alternative performance matrix is represented in Table 4. The rating of alternative *i* with respect to criterion *j* is represented by X_{ij} and w_j is the weight of criterion *j* (the rating of alternative *i* with respect to criterion *j* is assumed non-negative). The criteria weights from the material selection process are responsible for the selection rankings.

Table 4. Configuration of the Alternative Performance Matrix

	Criterion 1	Criterion 2	…..	Criterion n
Alternative 1	X_{11}	X_{12}	…..	X_{1n}
Alternative 2	X_{21}	X_{22}	…..	X_{2n}
:				
:				
Alternative m	X_{m1}	X_{m2}	…..	X_{mn}
	W_1	W_2		W_n

The probability of each element was distributed based on its probability function. The corresponding value *x* needed to be normalized for each criterion in order to gain the projection value of each criterion. The element of this matrix for jth criterion is shown in Eq. 1,

$$P_{ij} = \frac{x_{ij}}{\sum_{j=1}^{m} x_{ij}} \tag{1}$$

where, P_{ij} is the projection value of i according to j^{th} criteria, x_{ij} is the aggregated fuzzy rating, and m is the number of alternatives.

After normalized the corresponding value, the entropy value, e_j was calculated using Eq. 2,

$$e_j = -k \sum_{j=1}^{n} P_{ij} \ln P_{ij} \tag{2}$$

where, e_j is the entropy value, n is the number of criteria, and k is the number of decision makers where k is a constant (k = (ln(m))-1)).

The degree of divergence (d_j) of the basic information for each criterion was calculated by Eq. 3,

$$d_j = 1 - e_j \tag{3}$$

The final step in calculating Shannon’s entropy was to determine the weight using Eq. 4,

$$W_j = \frac{d_j}{\sum_{k=1}^{n} d_k} \tag{4}$$

where W_j is the subjective weight according to the j^{th} criteria.

Table 5. Comparable Data of Starch Alternatives Gathered

Properties	Unit	Wheat	Maize	Potato	Cassava	Sago	Rice
Amylose	%	26-27	26-28	20-25	17	24-31	24-37
Amylopectin	%	72-73	71-73	74-79	83	75	64.49
Protein Content	%	0.3	0.3	0.05	0.1	0.19-0.25	0.25-0.3
Moisture Content	%	13	12-13	18-19	13	10-20	10-12
Granule Diameter	µm	21.9-22.8	9.4-15	45-50	12.1–16.3	10-50	1.1-8
Ash	%	0.2	0.1	0.4	0.2	0.06 - 0.43	0.05-2.0
Density	g/m^3	1.44	1.5	1.54-1.55	1.446-1.461	0.17	1.53
Raw Cost*	-	7	6	7	5	2	6
Availability*	-	6	6	6	6	8	7

* Raw cost and availability are evaluated based on a subjective evaluation that depended on the structure, origin, and global market price of the starch. Scores of 1 to 9 (low to high) were given for each starch to show the level of the properties compared with one another (Mastura et al. 2018). Data were retrieved from Swinkles (1985); Hamanishi *et al.* (2000); Gurunathan *et al.* (2015); Sanyang *et al.* (2016); Hsieh *et al.* (2018); Grommers *et al.* 2009; Karim *et al.* (2008); Adawiyah *et al.* (2013); Amagliani *et al.* (2016); Wani *et al.* (2012); Oko (2012); Abdul Alam (2018).

The characterization and properties of the selected starches could have been obtained *via* experimental work in order to get more accurate data. However, due to limited time and resources, this is beyond the scope of this study. Therefore, the data was collected from recent and prominent literature on starches' characteristics. Restrictions in the availability of comparable data for different types of starches also limited the number of alternatives that could be considered for this study. Data on the attributes and characteristics of six starches from different plant sources were obtained; therefore, only these starches were able to be assessed. These starch candidates are shown in Fig. 4, sorted by their classification. The data gathered on the starches is shown in Table 5.

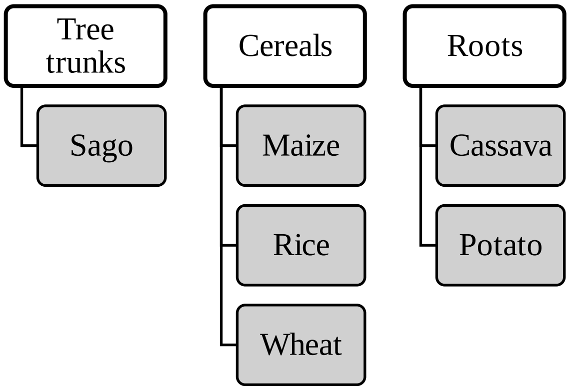


Fig. 4. Starch candidates in the selection process for food packaging design according to their classification

RESULTS AND DISCUSSION

Criteria Weighing *via* Shannon's Entropy Method

The response data matrix, comprised of the responses from the 15 experts (as shown in Appendix I), was processed *via* the use of Shannon's entropy method in order to evaluate the 10 sub-criteria. Utilizing Eq. 2, Eq. 3, and Eq. 4, respectively, the entropy value (e_j), the degree of divergence (d_j), and the entropy weight (W_j) for each evaluation index was calculated. The criteria of the greatest importance, in terms of weight, is the one that has most information available (Ishak *et al.* 2017). The computed results found that all the sub-criteria had approximately equal weights, with a slight difference in values. Table 6 presented the entropy values (e_j), the degrees of divergence (d_j), and the entropy weights (W_j) calculated for each criterion. Figure 5 shows the performance of the entropy weights for all the determined attributes as starch selection criteria. Amylose has the highest weight value, followed closely by amylopectin and protein content. Availability, water content, and raw cost are the next highest weight with small difference in weight values. Density is just slightly lower, but more than ash. Granule diameter has the lowest weight of all the criteria with only 0.0002 difference.

However, the weight values obtained for the nine attributes were not the final weights. The weight values that were used in the selection system were determined by multiplying the weight values of each attribute with the weight value of the primary criteria associated with them.

Table 6. Entropy Value (E_j), Degree of Divergence (D_j), and Objective for Each Criterion

Criteria	Criterion Index	Entropy Values (e_j)	Degree of Divergence (d_j)	Weight (W_j)
Amylose (%)	C1	0.212155114	0.787844886	0.12343876
Amylopectin (%)	C2	0.217919408	0.782080592	0.12253562
Protein Content (%)	C3	0.230578209	0.769421791	0.12055225
Moisture Content (%)	C4	0.312756881	0.687243119	0.10767658
Granule Diameter (µm)	C5	0.347930605	0.652069395	0.10216559
Ash (%)	C6	0.346802578	0.653197422	0.10234233
Density (g/m3)	C7	0.334391481	0.665608519	0.10428689
Raw cost	C8	0.315005527	0.684994473	0.10732426
Availability	C9	0.299984709	0.700015291	0.10967771

Fig. 5. The entropy weights of the nine selected properties of starch

Table 7 shows all the weight values for the primary criteria and the sub-criteria.

Table 7. Primary Criteria and Sub-Criteria Weight Values

Primary Criteria	Weight	Sub-Criteria	Global Weight	Local Weight
Strength	0.25	Amylose	0.1234	0.2634
		Amylopectin	0.1225	0.2614
		Protein content	0.1206	0.2572
		Granule diameter	0.1022	0.2180
Barrier property	0.25	Moisture content	0.1077	0.5127
		Ash	0.1023	0.4873
Weight	0.25	Density	0.1043	1.0000
Cost	0.25	Raw cost	0.1073	0.4946
		Availability	0.1097	0.5054

Regarding the attributes classified under strength, the amylose and amylopectin have about similar weight, *i.e.* 0.2634 and 0.2614, whilst weight value for protein content is 0.2572 and granule diameter is 0.2180. For barrier property criteria, both sub-criteria have a slight difference in their weight values, *i.e.* 0.512 (moisture content) and 0.4873 (ash). Two sub-criteria under cost too have approximately equal weight values, raw cost (0.4946) and availability (0.5054).

AHP and Expert Choice Software Results

The AHP hierarchy structure proposed in Fig. 2 was generated and displayed *via* Expert Choice software, as displayed in Fig. 6.

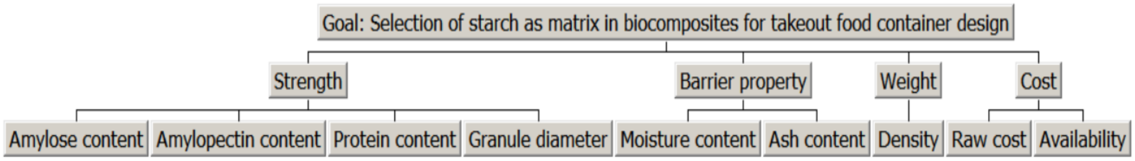
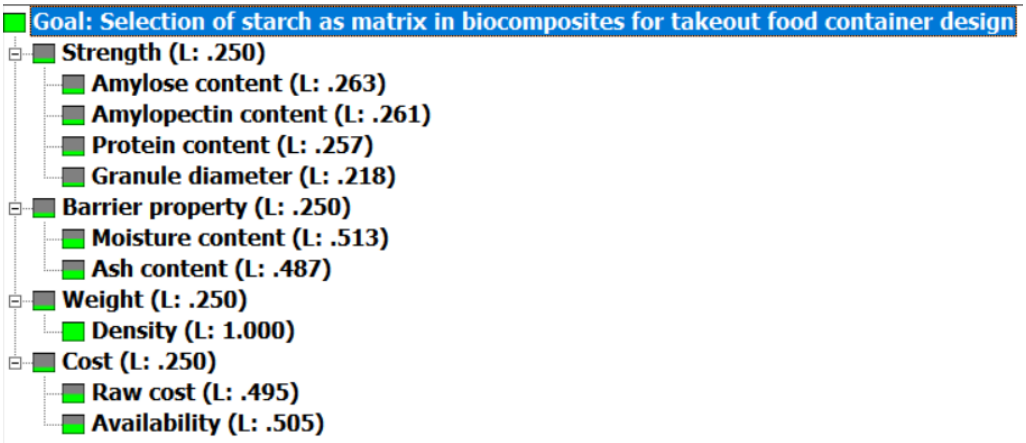


Fig. 6. Hierarchy structure developed in Expert Choice Software (not including the alternatives)

All the weight values in Table 6 were inserted directly into a specified column in the Expert Choice software, and the recorded weights values were displayed in the structure developed by the software (Fig. 7). The starch alternatives were also entered into the provided column in the software. Pairwise judgements at the alternative level (as listed in Table 2) were individually compared in pairs, with respects to all the sub-criteria. The judgment values for each assessed pair were based on the comparison ratio technique, as demonstrated by Sapuan *et al.* (2011). For example, ash content for maize is 0.1% and potato is 0.4% therefore the ratio of maize to potato is 0.4:0.1 which is equal to 4.0 (the calculation was reversed so that assigned value was greater than 1) but lower ash content is preferable for lower porosity and water permeability, a good barrier property. So, the assigned value of relative importance of maize when compared to potato with respect to barrier property is 4.0 and the scale used was to the left (black scale number). Another example, the amylose value of wheat was 27% and for maize is 28%. Therefore, the ratio of wheat to maize is 28:27, which equaled a value of 1.037 (the calculation was reversed so that assigned value was greater than 1).



Goal: Selection of starch as matrix in biocomposites for takeout food container design
- Strength (L: .250)
  - Amylose content (L: .263)
  - Amylopectin content (L: .261)
  - Protein content (L: .257)
  - Granule diameter (L: .218)
- Barrier property (L: .250)
  - Moisture content (L: .513)
  - Ash content (L: .487)
- Weight (L: .250)
  - Density (L: 1.000)
- Cost (L: .250)
  - Raw cost (L: .495)
  - Availability (L: .505)

Fig. 7. AHP structure with criteria weights obtained *via* Shannon's entropy method

Since amylose content of maize is higher, thus preferable than wheat for greater strength and toughness of material, the assigned value of relative importance of wheat when compared to maize with respect to amylose was 1.037. Therefore, the red colour scale (to the right) was assigned in the software. The pairwise judgement matrices, with respects to all the sub-criteria, are shown in Appendix II.

In relation to the goal of the study, the AHP results generated by the software displayed the priority values of the alternatives and generated ranks for the starches, in terms of the right starch as matrix in biocomposites for takeout food container design as shown in Fig. 8. The results show that the top ranked starch *i.e*. sago, has a priority value significantly higher (0.268 or 26.8%) than the other starches. The second highest ranked starch is rice starch with a priority value of 0.202 (20.2%). Next in order are maize starch, wheat starch, and cassava starch with priority values of 15.5%, 14.1%, and 13.0%, respectively. Potato starch is at the lowest rank with a priority value of 0.105 (10.05%).

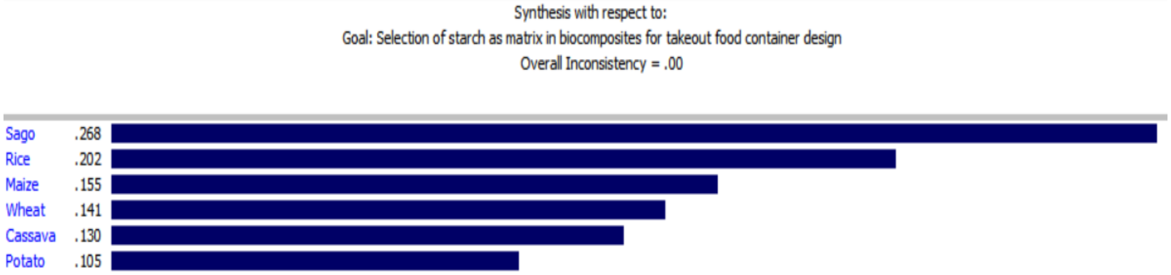


Fig. 8. Results with respect to goal of study generated by Expert Choice Software

The outcomes generated by the software were further explored and the priority values with respect to each primary criterion of the starch alternatives were examined. Figure 9 summarized the performance of the starch alternatives. With respect to the strength criteria, rice starch had a higher performance when compared to the other starches. Wheat, maize, and sago had about the same accomplishment but were still higher than cassava and potato.

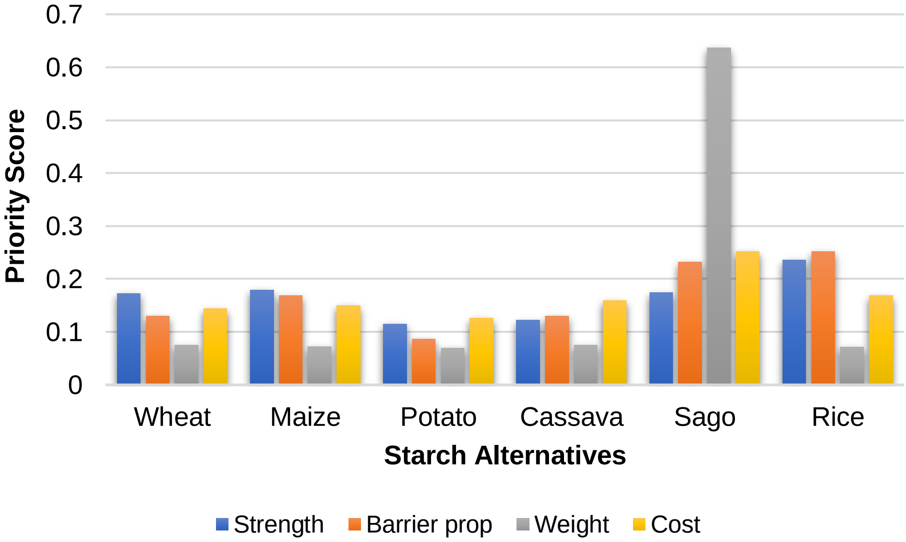


Fig. 9. Performance of each starch with respect to the main criteria

For the barrier property, rice and sago have about similar priority values and are higher than the other starches. Potato has the lowest performance value in this criterion whereas, with respect to weight criteria, sago starch has the highest priority values with an obvious difference than the other starches which have approximately similar performance. Finally, for cost criterion, sago achieved slightly higher than other starches.

Sensitivity Analysis

Sensitivity analysis is the concluding process for the AHP method and for Expert Choice software. It is a critical step in verifying the results, in order to determine whether they are feasible and robust. The core objective of performing the sensitivity analysis was to verify the decision of the material selection process, by studying how different factors under different circumstances would affect the results. Six different scenarios were tested where the weight values of the primary criteria were altered. Figure 10 combined all the results for the six altered conditions and was generated *via* Expert Choice software.

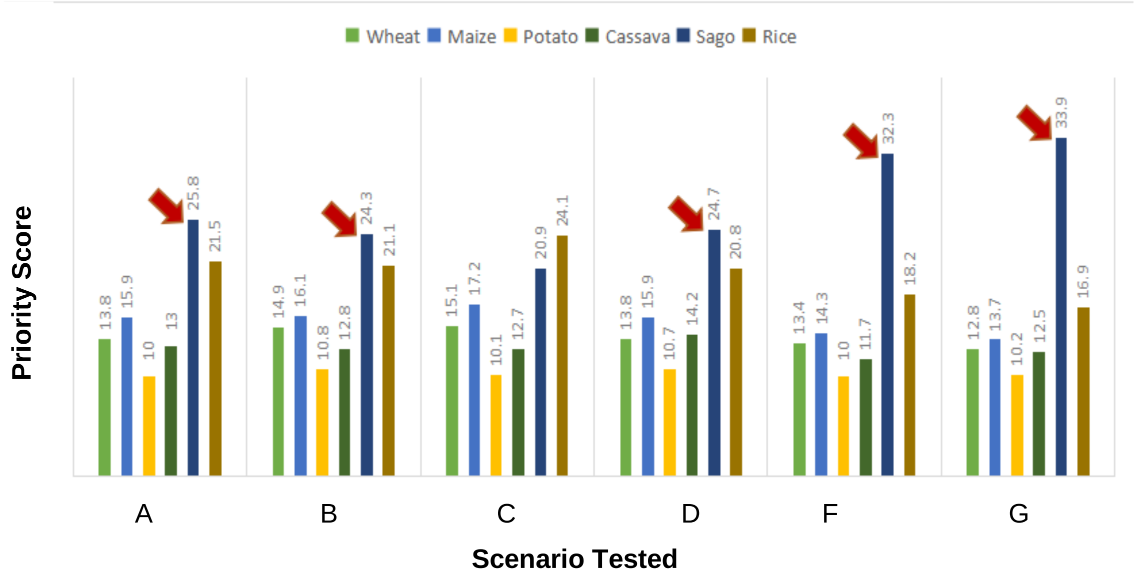


Fig. 10. Sensitivity analysis results of the six different circumstances (A. Increase 20% of barrier property; B. Increase 20% of strength; C. Increase 10% of both strength and barrier property; D. Increase 10% of both strength and weight; E. Increase 10% of both barrier property and cost; F. Increase 10% of both weight and cost)

The results of the AHP model were influenced by the varying values of the priority vector of the primary criteria throughout the sensitivity analysis performance. Therefore, the final verdict of the most suitable starch for packaging utilization was decided after the sensitivity analysis for the six scenarios was conducted. Six different scenarios were tested, in which the weight values of the primary criteria were altered, as followed: (A) a 20% increase in the weight value of the barrier property; (B) a 20% increase in the weight value of strength; (C) a 10% increase in the weight values of both strength and barrier property; (D) a 10% increase in the weight values of both strength and weight; (E) a 10% increase in the weight values of both barrier property and cost; and (F) a 10% increase in the weight values of both the weight and cost criteria.

The sago starch alternative held the top rank in five out of the six simulated scenarios (noted with red arrow in Fig. 10). Interestingly, only in scenario C where weight values of strength and barrier property were increased 10% from the initial weight, sago fell into second rank after rice starch. By synthesizing results in terms of the barrier property and strength (Fig. 9), rice starch was found to have a greater performance than sago for both criteria. Hence, with higher weight for these two criteria, rice starch obtained higher priority values. Notably, other starches *i.e.* wheat, maize, cassava, and potato starches had remained at the same rank position for all scenarios tested. Potato consistently stayed at the lowest rank. Consequently, sago, rice and maize starch were considered to be the first three alternatives for the selection of starch as matrix in green biocomposites for a takeout food container design application.

Sago is extracted from trunks of palm trees, and rice is a cereal starch like maize and wheat. On the other hand, cassava and potato are taken from roots of their botanical plants and are the least preferable choice in this selection system. From this result, the classification of starch according to their origin in plants might be an interesting analysis to explore regarding its relationship with suitability in a specific application.

It is also important to note that the weights obtained for the sub-criteria indicate their priority value. Certain attributes have a higher priority, *i.e.*, greater importance, over the other attributes. As determined from analysis of the performance of each starch, with respect to each primary criterion, rice starch outscored the other starches in terms of strength and barrier property but was not assigned at the top overall ranking. Whereas for the weight criterion, sago starch obtained the highest value significantly and had the highest final ranking. Moreover, sago starch also performed higher than the other starches for cost criterion. It can be concluded that the weight criterion with only one sub-criteria, namely density, were the leading indicators that pushed sago starch into the highest rank, with respect to the goal of this study.

Nevertheless, the AHP method could only provide prioritization scoring of the alternative starches and does not identify the success-critical factors and their corresponding requirements (Ahmad *et al.* 2010). For this starch selection framework, the establishment of the selection criteria was critical and must be accurately defined according to the specific requirements, since it was shown to affect the results of the selection. The criteria chosen in this selection system could be more comprehensive with more starch attributes and characterization of thermoplastic starch films that are worthy of being evaluated for the making-decision process. According to the report of Ortega-Toro *et al.* (2017), the method used and the type and amount of applied plasticizers could affect the final mechanical and thermal characteristics of the starch-based materials developed. Trustworthy and accountable sources of starch's characterization data also played a major role in this selection process, since there is a lack of established commercial databases on the different type of starches. By gathering characteristics data from literature for the starch alternatives limited the number of alternatives that were able to be evaluated in this work of study.

CONCLUSIONS

1. This work was able to apply the Analytic Hierarchy Process (AHP) method combined with Shannon's entropy method successfully. This proposed framework would assist designers or material engineers in effectively determining the most suitable starch for food packaging utilization, using a combined approach of Shannon's entropy method and AHP.

2. The AHP *via* Expert Choice software was utilized to evaluate the starch alternatives and the results revealed that sago starch was the most appropriate starch as matrix in green biocomposites for takeout food packaging design application with overall priority scores of 26.8%. Rice starch with a priority value of 20.2% is the next best option and maize starch (15.5%). Potato starch is at the lowest rank with a priority value of 10.05%.
3. A sensitivity analysis was also conducted to further verify the decision, and it validated the results that sago starch was the first option where it scored the highest rank in five out of the six scenarios tested. The second-best option was rice starch. Potato starch was consistently at the lowest rank for all scenarios and therefore was the least preferred starch for the formation of starch biocomposites in takeout food packaging design.
4. Some inadequacies that were identified for this proposed selection system could be solved by incorporating more criteria and starch characteristics into the system such as the mechanical properties of the thermoplastics starch of different sources produced with the same methods with the used of the same plasticizers and amount. These features could be starch's crystallinity, strength, thermal properties, soil degradation, and most importantly, water and gas permeability of the starch. More starch alternatives from other various of plants sources could also be assessed to get more comprehensive results for takeout food packaging design.

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SUPPLEMENTARY
Appendix I

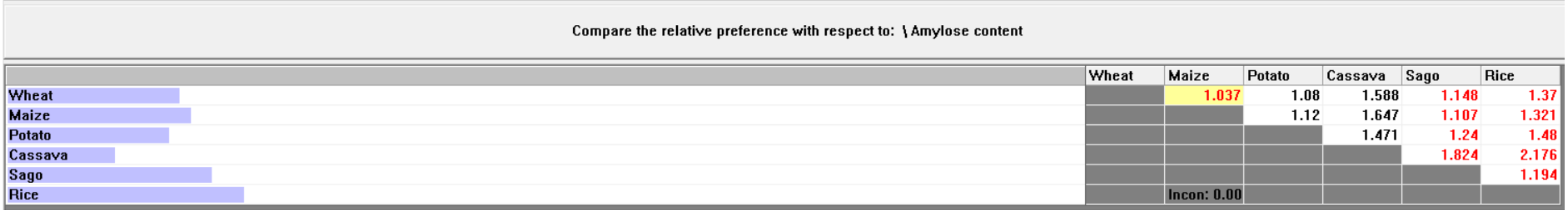
Table S1. Expert's Survey on Level of Importance of Each Starch Attribute

Starch Attributes	**Experts**															
		N1	N2	N3	N4	N5	N6	N7	N8	N9	N10	N11	N12	N13	N14	N15
Amylose (%)	C1	3	6	7	4	5	7	5	6	5	4	7	5	5	6	4
Amylopectin (%)	C2	3	5	7	4	6	7	5	6	5	3	7	3	5	6	4
Protein Content (%)	C3	3	4	7	4	7	7	5	6	2	3	2	5	5	5	5
Moisture Content (%)	C4	6	6	7	7	7	7	6	6	6	7	4	4	4	5	6
Granule Diameter (µm)	C5	6	6	6	7	2	7	5	5	2	7	1	6	2	5	7
Ash (%)	C6	5	5	7	7	5	7	5	6	1	3	1	2	2	4	2
Density (g/m3)	C7	6	6	7	7	3	7	6	7	3	7	1	7	3	3	6
Raw cost	C8	6	7	7	7	5	4	6	5	7	7	7	5	4	5	5
Availability	C9	6	7	7	7	5	4	6	5	7	7	7	6	6	7	7

Appendix II

Strength

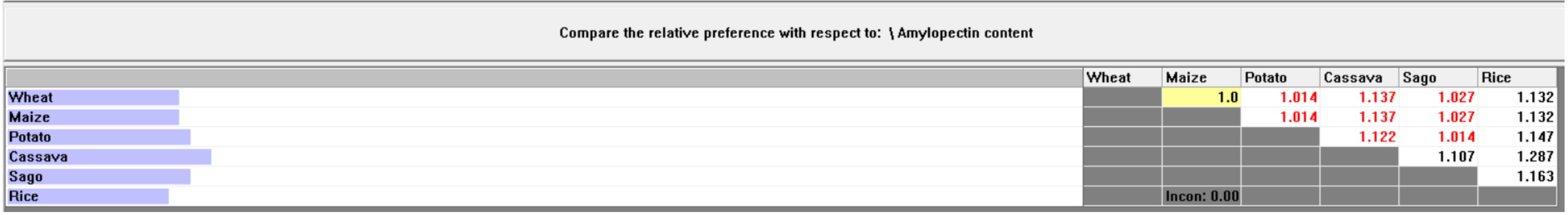
A. Amylose



Compare the relative preference with respect to: \ Amylose content

	Wheat	Maize	Potato	Cassava	Sago	Rice
Wheat		1.037	1.08	1.588	1.148	1.37
Maize			1.12	1.647	1.107	1.321
Potato				1.471	1.24	1.48
Cassava					1.824	2.176
Sago						1.194
Rice		Incon: 0.00				

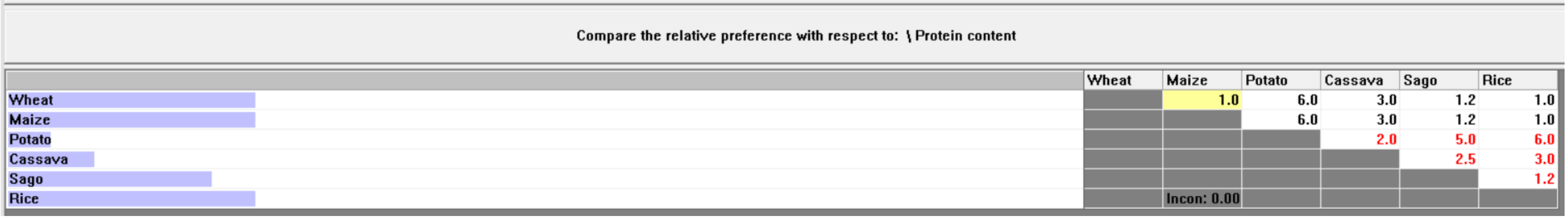
B. Amylopectin



Compare the relative preference with respect to: \ Amylopectin content

	Wheat	Maize	Potato	Cassava	Sago	Rice
Wheat		1.0	1.014	1.137	1.027	1.132
Maize			1.014	1.137	1.027	1.132
Potato				1.122	1.014	1.147
Cassava					1.107	1.287
Sago						1.163
Rice		Incon: 0.00				

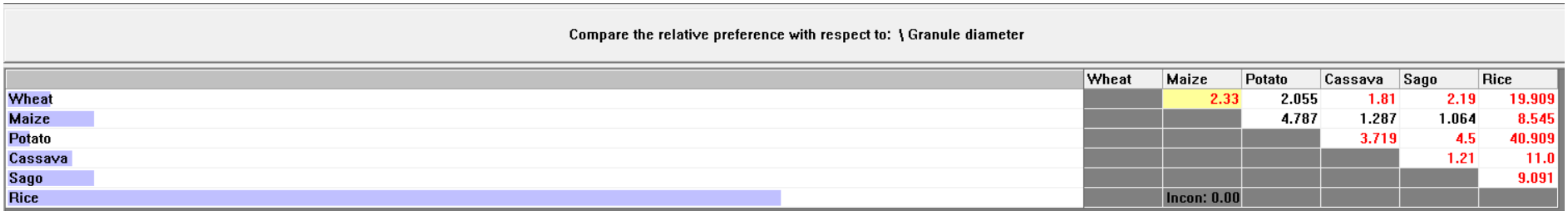
C. Protein content



Compare the relative preference with respect to: \ Protein content

	Wheat	Maize	Potato	Cassava	Sago	Rice
Wheat		1.0	6.0	3.0	1.2	1.0
Maize			6.0	3.0	1.2	1.0
Potato				2.0	5.0	6.0
Cassava					2.5	3.0
Sago						1.2
Rice		Incon: 0.00				

D. Granule diameter



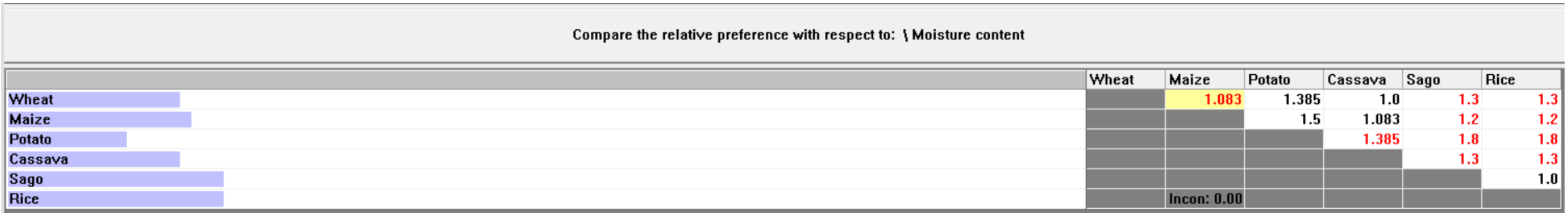
Compare the relative preference with respect to: \ Granule diameter

	Wheat	Maize	Potato	Cassava	Sago	Rice
Wheat		2.33	2.055	1.81	2.19	19.909
Maize			4.787	1.287	1.064	8.545
Potato				3.719	4.5	40.909
Cassava					1.21	11.0
Sago						9.091
Rice		Incon: 0.00				

Fig. S1. Pairwise comparison matrices of starch alternatives with respect to each sub-criterion; A. Amylose; B. Amylopectin; C. Protein content; D. Granule diameter

Barrier property

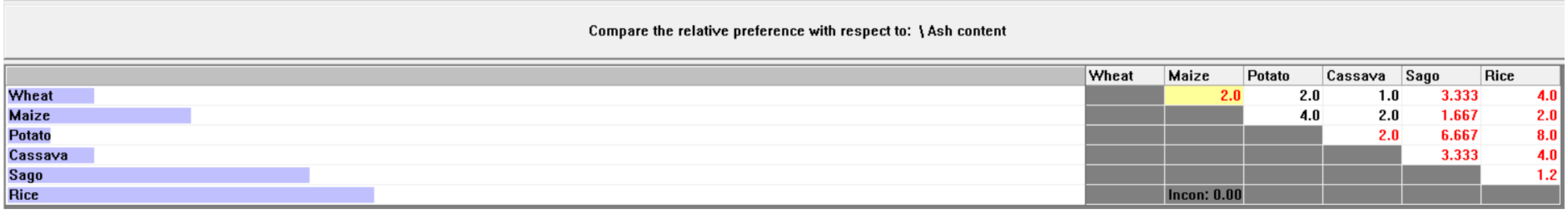
A. Moisture content



Compare the relative preference with respect to: \ Moisture content

	Wheat	Maize	Potato	Cassava	Sago	Rice
Wheat		1.083	1.385	1.0	1.3	1.3
Maize			1.5	1.083	1.2	1.2
Potato				1.385	1.8	1.8
Cassava					1.3	1.3
Sago						1.0
Rice		Incon: 0.00				

B. Ash



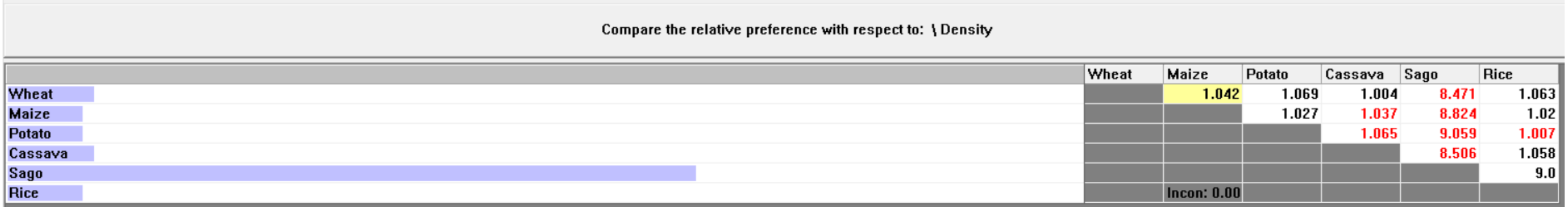
Compare the relative preference with respect to: \ Ash content

	Wheat	Maize	Potato	Cassava	Sago	Rice
Wheat		2.0	2.0	1.0	3.333	4.0
Maize			4.0	2.0	1.667	2.0
Potato				2.0	6.667	8.0
Cassava					3.333	4.0
Sago						1.2
Rice		Incon: 0.00				

Fig. S2. Pairwise comparison matrices of starch alternatives with respect to each sub-criterion; A. Moisture content; B. Ash

Weight

Density



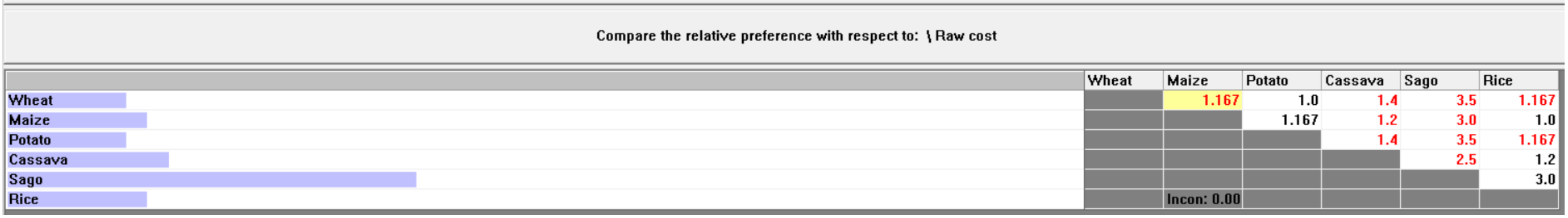
Compare the relative preference with respect to: \ Density

	Wheat	Maize	Potato	Cassava	Sago	Rice
Wheat		1.042	1.069	1.004	8.471	1.063
Maize			1.027	1.037	8.824	1.02
Potato				1.065	9.059	1.007
Cassava					8.506	1.058
Sago						9.0
Rice		Incon: 0.00				

Fig. S3. Pairwise comparison matrices of starch alternatives with respect to each sub-criterion: Density

Cost

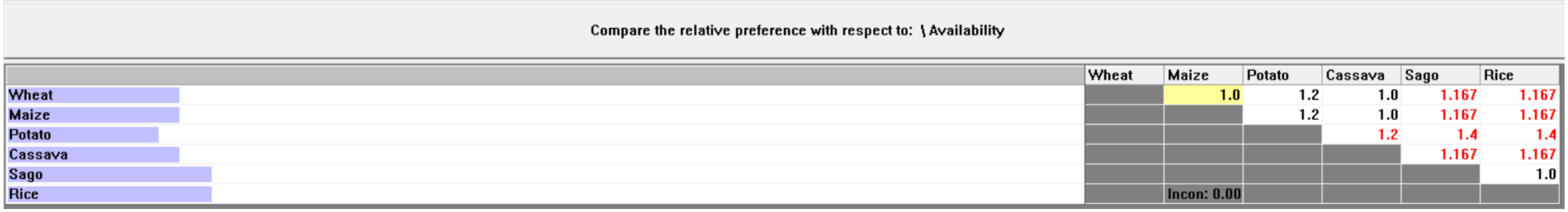
A. Raw Cost



Compare the relative preference with respect to: \ Raw cost

	Wheat	Maize	Potato	Cassava	Sago	Rice
Wheat		1.167	1.0	1.4	3.5	1.167
Maize			1.167	1.2	3.0	1.0
Potato				1.4	3.5	1.167
Cassava					2.5	1.2
Sago						3.0
Rice		Incon: 0.00				

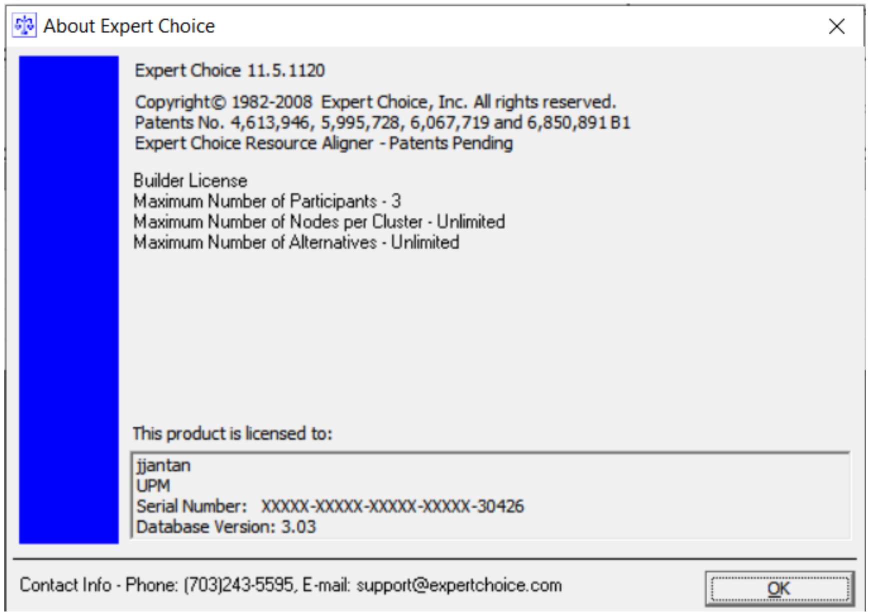
B. Availability



Compare the relative preference with respect to: \ Availability

	Wheat	Maize	Potato	Cassava	Sago	Rice
Wheat		1.0	1.2	1.0	1.167	1.167
Maize			1.2	1.0	1.167	1.167
Potato				1.2	1.4	1.4
Cassava					1.167	1.167
Sago						1.0
Rice		Incon: 0.00				

Fig. S4. Pairwise comparison matrices of starch alternatives with respect to each sub-criterion; A. Raw cost; B. Availability



Expert Choice 11.5.1120

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Expert Choice Resource Aligner - Patents Pending

Builder License
Maximum Number of Participants - 3
Maximum Number of Nodes per Cluster - Unlimited
Maximum Number of Alternatives - Unlimited

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Fig. S5. Expert choice software specifications (https://www.expertchoice.com/ahp-software)