The Structural Design of 3D Printed Bottle Prototype using a PLA Based Eco-friendly Polymer Packaging Material

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Abstract:
Packaging materials research areas have a great concerned to develop and create attractive packaging item with eco-friendly and health impact. There is still an urgent need to establish innovative design and production standards that attract the eyes of the consumer, and these standards must be cost-effective and for the production. So this study aims to ergonomic science applied to design comfortable packaging bottle with easy drinkable and handling easily and using future environmentally friendly materials in the world of packaging. 3D printing technology was used to produce three bottle designs with a 45° inclination angle produced from polylactic acid (PLA) filament as biodegradable and eco-friendly polymer. The 3D printed bottles are designed as a prototype for the consumer. Three PLA bottles were investigated as acceptable packaging materials with mechanical properties, overall migration and migrated toxic heavy metals detection. The samples were analyzed for heavy metal content per ASTM E1613-04 where overall migration was measured according to EC 2011/10. Tensile strength and elongation at break exhibited good physico-mechanical properties with for 43 MPa and 4.6 %, respectively as hard packaging item. The overall migration was acceptable according to EC 2011/10. In addition, migrated heavy metals detection shown tiny value as ≥ 0.3 ppm. Designing bottles were digitally printed to add a logo on bottle beside printed paper sticker. Moreover, statistical questionnaire scanning was shown a great acceptable percentage with more than 83% for designing, printing and easy use of produced bottles. 3D printing, ergonomic design and packaging materials research fields are combined to create sustainable packaging bottle for easy and health use.

Keywords:
Structure Design**,** Hard Packaging, Overall Migration (OM), 3D Printing, Easy Drinkable, Ergonomic Packaging

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Introduction
In today's increasingly competitive market, satisfying the needs and tastes of consumers has become a major concern for nearly every company. For that, many companies have turned to design Innovative products gaining new markets; relate to competition[1]. In addition to the marketing aspect, prospective designed packages should meet the needs of consumers in terms of function, appearance, and cost. Whereas, packaging design, whether it is structural design or graphic design, plays an important role in package marketing[2]. Hard packaging is the most interested trend of researching through a new application in the field of packaging. There are wide field of applications for hard packaging in juice, milk, water, liquid detergent …. etc.[3].

The design of the water bottle is characterized by comfortable aspects of packaging in terms of easy of handling, drinking, opening and closing the package[4]. Where aesthetic and functional values were taken into account in the design technologies associated with production, and the end use of the product[5]. The innovative ergonomic design has an angle 45° degree of inclination for easy drinking[6]. There are many program designs like, Fusion 360, Auto CAD, Rhino, Solid Edge, and Pro Engineer. Where the Solid Work program was used in the design as it is one of the distinguished programs in the field of industry, (CAD) Computer-aided design, (CAM) computer-aided manufacturing[7]. Printing designs in 3D printing as a distinct new technology that can produce a wide range of packages specification[8]. Producing a package sample simulate the real specific with specific designs is gaining popularity especially due to the fact that this is a rapid prototyping and small-scale manufacturing technology[9].

3D printers use many materials, including acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA)[10]. PLA is one of biodegradable and ecofriendly polymer with

various advantages that avoiding the free radical presence in the regular packaging that causes cancer an innovative material[11]. Using biobased polymers in a wide range of markets from packaging, a versatile biodegradable polymer made from annually renewable resources[12].

Migration of packaging materials has a great interesting corner in industrial and research corresponding to health issue[13]. The packaging material, low molecular weight substances may diffuse through the bulk polymer subsequently migrate into the foodstuff[14]. In industrial scale, there are many additives can be migrated from bulk polymer layer in addition to polymer chains[15]. In 3D printing, the migration is mainly related to polymer staff[16]. Healthy impact can be supported the application of biodegradable polymers as packaging materials with novel ergonomic design with attractive easily application[17].

Research problem

- Using of polyester material (petroleum -based polymers) currently applied on the market at a high risk migration rate.
- Hazardous compounds from polyester and polyethylene terephthalate packaging were migrated to the packaged products.
- The current structural design gives uncomforting feeling to the users that caused by the mouth of a bottle in the middle of the water bottle.

Research Importance

In this paper, replacement of ecofriendly and biobased packaging materials instead of petroleum-based polymers is the great challenge in environmental and packaging research area over the world. The ergonomic design of the new structural bottle with 45^{o} inclination angles was printed as a prototype for the customer. PLA material was investigated as an environment friendly material with good great mechanical properties.

Objectives:

This research is aims to replacing environmental friendly biobased packaging materials PLA instead of petroleum -based polymers that available in market. In addition, new structure bottle was designed with 45^{o} inclination angle and printed by 3D technology. For that, verification of PLA as an environmental friendly packaging material by studying its mechanical properties, permeability, heavy metals and overall migration were carried out

Research hypotheses

The research assumes:

1- The effectiveness of an environmental friendly PLA polymer which can be used as future packaging material.
2- The effectiveness of the structural design of the bottle at an angle of 45° for easy drinking.
3- Providing an environmental friendly future material for the Egyptian packaging market in addition to a new structural design suitable for packaging various products.
4- Presenting a prototype to the customer printed with a sticker that is better than printing directly on the bottle.
5- The approval of the manufacturers and the costumer for this type of bottle with a new structural design and a 45^{o} degree -tilted angle and new material PLA will be prospected as future packaging material.

Originality / value:

This research work is related to high-value industrial packaging material PLA. It replaces the dangerous petroleum based polymer, avoiding the presence of free radicals or metal oxide in normal packaging. Dangerous compounds can cause cancer and organ failure. On the other hand, an innovative material has been applied and a convenient packaging bottle has been designed with an angle of inclination of 45° degrees with ease of drinking and handling.

Research tools

- 3D printer
- PLA material
- 10% ethanol, 3% acetic acid and olive oil.
- Optical Emission Spectrometer (ICP-OES)
- UJF-6042MK printer
- canon Image press c 10000 vp,
- (X-Rite, Pantone, USA)(spectrophotometer)
- Contained statistical study the sample was included researchers group divided into 30 faculty members at the college of Applied Arts, department of printing, publishing, and packaging, and the department of industrial design. In addition, 10 factories owners of bottle production, and 20 consumers of the product were examined.

Literature Review:

3D Printing in packaging:

3D printing in packaging is an emerging technology with applications in several areas. The flexibility of the 3D printing system to use variety of materials and create any object makes it an attractive technology. 3D printing is cheap and produces little waste, which also gives it an ecological advantage. 3D printing also allows for very complex geometries, which in many cases is an area where no other manufacturing methods can compete. The 3D printing technology is

superior in speed when many unique pieces.

Packaging material (PLA)

PLA polymer is environmentally friendly, basically derived from corn starch and therefore and has distinct mechanical properties. One of its advantages is that it avoids the free crack found in normal packaging that causes cancer, is an innovative material used in a wide range of markets of packaging, and is a versatile and biodegradable polymer made from renewable resources. Being biodegradable it provides a valuable contribution to the circular economy, products can be mechanically or chemically recycled produced from plant material and is fully renewable and recyclable [12].

packaging in Europe

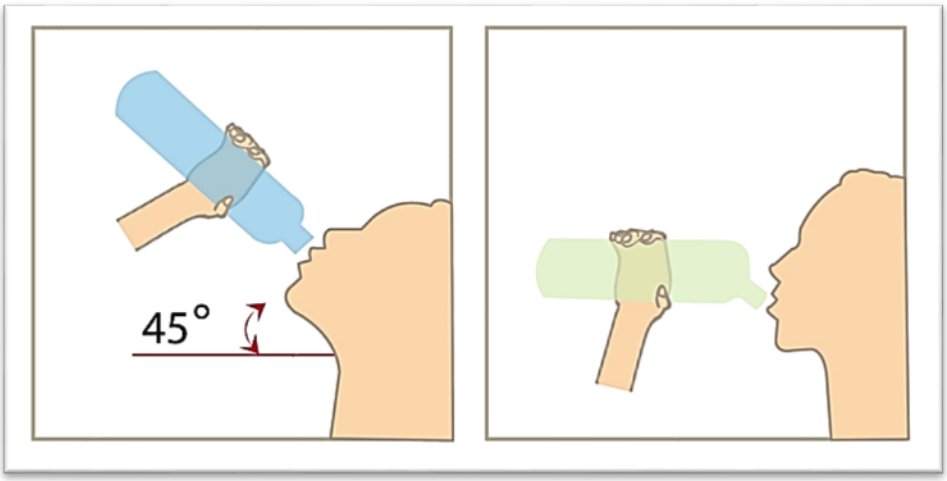
PLA offer a reduced carbon footprint versus many traditional plastics. It provides valuable contribution towards the circular economy being biobased and biodegradable with nice mechanical properties[18]. products can be mechanically or chemically recycled produced from plant material and is fully renewable and recyclable[19].

Scheme1: PLA

Structure design bottles with 45 angle:

Structure design was carried out to achieve quality of design and production processes in terms of providing a comfortable working environment for users according to physical measurements of human body, ergonomic packaging.

The structure design bottles with 45 angles (Easy Drink) in a way that improves users' neck uncomforting when drinking water, easy drinking, comfort for the vertebrae of the neck, and easy refilling of the bottle [20]. (Scheme 2).



Scheme 2: illustration design of 45 angle bottles (Easy Drink)

2. Experimental and Methodology

In order to achieve the research objective, an experimental study is conducted as following:

2.1. Materials and methods

1- The structure design bottles were based on the program computer-aided design (CAD) Solid Works 2019.

2- Zortax M300 plus 3D printer, Poland, was used to print the three designed bottles 650 ml Universal 3D printing filament, PLA was purchased from Zortax with average diameter 1.75 mm.

The following designs (Figure (1a) / Figure (1b) Figure (1c)) the 45° degree inclination PLA packaging bottles were applied according to the ergonomic aspects of the packaging, including the photorealistic texture to prevent the bottle from slipping as well as easy of griping and handling, choosing the dimensions, shape and curves of the design was reflected average standard sizes available for bottle products in the Egyptian market [21]

The structure designs bottles as following:

- Shows the design Figure (1a) the bottle was supported with decorative cup to be easily drinking for children and can be saving to more than one person drinking from one bottle as healthy impact In addition, The design of the bottle cap has polygonal lines texture, as well as two protrusions appearing on the upper outer surface of the bottle for easy opening and closing of the bottle. This extrusion is suitable for anatomy of hands and this extrusion is

suitable that does not conflict or increase the cost of molds in mass production and can be implemented in industry easily.

Figure (1a) shows the different ergonomic structure designs

- Shows the design Figure (1b) the bottle with a 45° inclination angle, as well as fingerprint-like details and configurations for easy handling and anti-slipping.

Figure (1b) shows the different ergonomic structure designs

- Shows the design Figure (1c) of the bottle with a 45° inclination angle with special design forms to avoid slipping from hand. And recesses as an aesthetic shape of the bottle and to support the structural design and prevent slipping.

3- Mechanical properties, Tensile strength (TS) and elongation at break (E) of material were measured by Zwick/RoellZ020 instruments, (Ulm, Germany).

Figure (1c) shows the different ergonomic structure designs

4- Overall migration test was carried out with three simulants, 10% ethanol, 3% acetic acid and olive oil, and incubated for 10 days at 40°C. [22].

5- Total heavy metals test were performed in overall migration simulants, measurement concentration of most toxic heavy metals, using an device Agilent 5100 Inductively Coupled Plasma – Optical Emission Spectrometer (ICP-OES) [23].

6- The logos were printed with two different techniques to enhancement the quality and controls in the size of logo:

- Direct printing of bottle, was used to print 4-color logos directly onto the bottle for Logo was printed with UJF-6042MK printer, Japan with ink purchased from Mimaki, Japan – LUS-120. (Figure 3)
- The logo was printed on sticky paper (self-adhesive paper) 150g with canon Image press c 10000 vp, Japan. (Figure 4)
- The design in both cases contained a QR carrying information about the product and material for example , (PLA, poly lactic acid bottle is eco-friendly and biodegradable polymers as safety packaging material and as an added value to the labels printing).

8- The rate of color change ΔE (using color values L, a, b) was measured on the logo printed on adhesive paper (figure 4). Using a device (X-Rite, Pantone, USA) (spectrophotometer).

2.2. Results and Discussion

2.2.1. Mechanical properties

The mechanical testing of 3D printed dumbbell shape was illustrated in Figure 2 through measurement the tensile strength (TS) and

elongation at break (E). The PLA dumbbell shape was presented the TS and E for 43 MPa and 4.6 %, respectively, these results are within the permissible limits according to the ASTM-D412

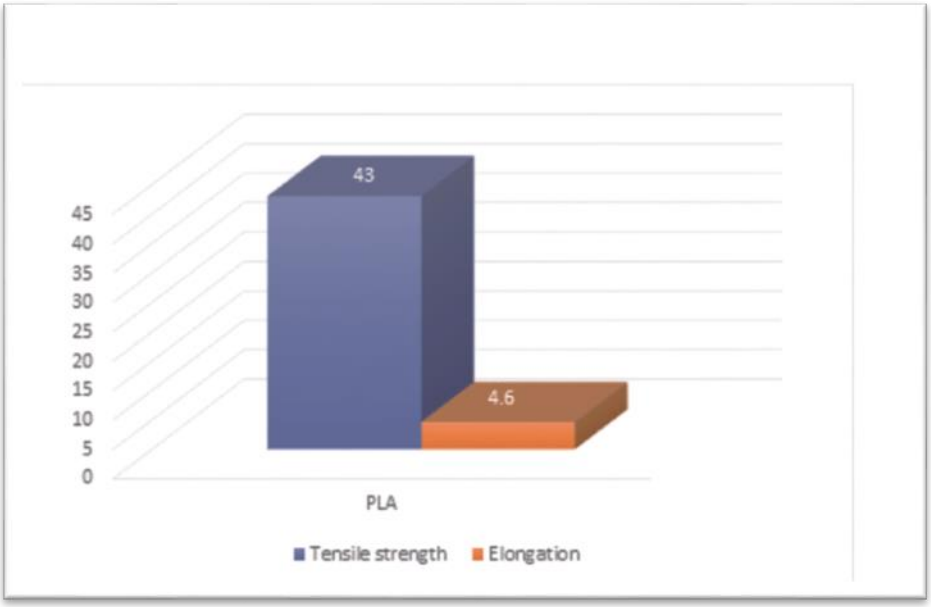


Figure2. The measurement the tensile strength (TS) and elongation at break (E)

The measurable mechanical properties of PLA were agreement with most polymeric materials used in bottle production as hard packaging materials [24].

From the results of Figure 6, the first hypothesis of the research is realized

2.2.2. The overall migration

The migration of any chemical substances from the 3D printed bottles has been studied according to the EU Regulation Nr. 10/2011. The stimulants were selected carefully to represent different food natures like dairy products, juice, fried potatoes …etc.. As shown in Table 1, the 3D printed bottles showed acceptable migration limits. The overall migration (OM) from the PLA 3D printed bottles were ranged from 0.2 up to 6.4 mg/dm^2. The regulation limits the accepted level up to 10 mg/dm^2, Overall migration results were calculated according to (EN 1186-5-single side contact in cell test) [25].

The following table1 shows the results of test (OM):

Method	***EN-1186-5***	***EN-1186-5***	***EN-1186-4***
Replicates	**Migration into 10% v/v ethanol (simulant A) mg/dm^2**	**Migration into 3% w/v acetic acid (simulant B) mg/dm^2**	**Migration into Olive oil (simulant D_2) mg/dm^2**
1 Figure (1a)	5.4	6.5	0.1
2 Figure (1b)	5.7	6.3	0.3
3 Figure (1c)	5.9	6.4	0.2
Mean result	**5.7**	**6.4**	**0.2**
Limit	**10.0**	**10.0**	**10.0**

Table 1. The overall migration from PLA 3D printing bottle

2.2.3. Total heavy metals determination

The migration of heavy metals had been investigated. The traced metals were cadmium, lead, chrome, and nickel. Levels of migrating heavy metals are within tolerable limits according to Specification (APHA, 2017) [26].

The following table 2 shows the results of test heavy metals:

Table 2. The determination of migrated heavy metals traces in various simulants

	Metal	Conc., ppm	Toxic level*, ppm
1	**Cadmium**	**0.13**	**NMT 10**
2	**Lead**	**0.15**	
3	**Nickel**	**0.14**	
4	**Chrome**	**0.30**	
5	**Arsenic**	**0.10**	

* ASTM E1613-04

The results of the migration and heavy metals tests indicated that PLA is suitable as a food contact layer.

From the results of Table 1 and Table 2, the third hypothesis of the research is realized.

2.2.4. Printing properties

As shown in following figures, the logos were printed with two different techniques to enhancement the quality and controls in the size of logo, Direct printing of bottle, was used to print 4-color logo directly onto the bottle and The logo was printed on sticky. According to Figures 3 and 4, the digital printing of label is better than direct printed logo in the PLA bottle.

Figure 3. Direct printing of bottle

Figure 4. Digital printing on self-adhesive paper

Color change rate test ΔE was performed on four-color digital printed logo printing (Digital printing on self-adhesive paper Figure 5). The color values were applied in comparison with ISO 12647 to calculate the rate of color change.

Figure.5. Digital printing Logo on self-adhesive paper

As shown in Table 3, the results shown that, the colors are (cyan Δ1.71), (yellow Δ0.64), (magenta Δ2.95) and (black Δ2.57) colors. The rates of color change (ΔE) were present in the permissible limits according to ISO 12647. There are little differences in the magenta and black areas, while there is a slight difference in the yellow and cyan areas that is not noticed by the customer eye.

From the results of Table 3, the four hypothesis of the research is realized.

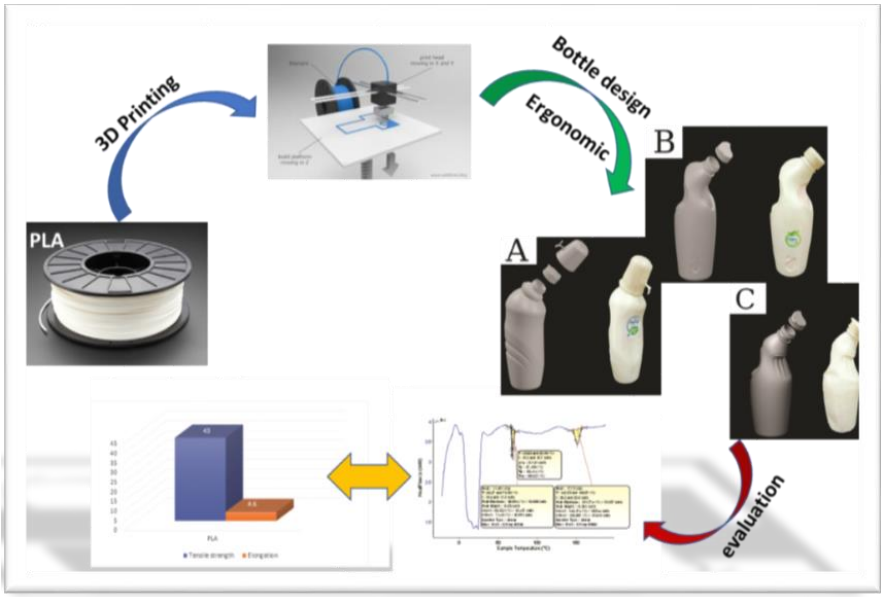
According to the previous results, the applied prototype bottle can be fulfilling all requirements for customer especially in creative design and attractive logo color.

Following display the obtained results:

Table 3. Illustrated the relation between CIE Lab color value for the main four colors

		L	A	B	
cyan ISO 12647	Target	55.18	-37.13	-50	ΔE
	sample	53.48	-35.72	-49.82	1.71
magenta ISO 12647	target	48.12	74.12	-3.01	ΔE
	sample	47.01	76.82	2.62	2.95
yellow ISO 12647	target	89.29	-5.02	93.16	ΔE
	sample	89.25	-4.21	90.5	0.64
black ISO 12647	target	15.01	0.19	-0.14	ΔE
	sample	14.25	1.88	0.78	2.57

The graphical abstract of research



Scheme3. The graphical abstract of research process and out come

2.2.5. Statistical Study

Preparation of a questionnaire sheet

A sample of opinions was taken via a two-dimensional questionnaire, by direct questions about the structural design of the bottles and printing as shown in Table 4 (supplementary). The sample was included researchers group divided into 30 faculty members at the college of Applied Arts, department of printing, publishing, and packaging, and the department of industrial design. In addition, 10 factories owners of bottle production, and 20 consumers of the product were examined. The results were analyzed by calculating the frequency and percentages of the response. The sample was divided onto individual dimensions using a test to determine the differences in the responses of the sample members.

Table 4. The question for all samples

		agree	moderate	Do Not agree
The first dimension: the structural design of the bottle (for all sample)				
Q1-1	How satisfied are you with the shape of the bottle with an inclination of 45 degrees			
Q1-2	The extent of your satisfaction with the functional ergonomics of the bottle			
Q1-3	How satisfied are you with the aesthetic ergonomics of the bottle			
Q1-4	How satisfied are you with closing and opening the bottle			
Q1-5	The extent of your evaluation of the design of the package cap that it contains two protrusions			
Q1-6	How satisfied are you with the ease of use and handling of the bottle			

The second dimension: the scale of the production and manufacture of the bottle and its printing (for staff and Factory owners)				
Q2-1	How do you evaluate the shape of the bottle when 3D printed			
Q2-2	It is expensive to manufacture such a new structural shape			
Q2-3	The shape of the bottle with 45 degree inclination is capable of marketing			
Q2-4	Direct printing on the bottle has achieved the product quality			
Q2-5	How good is the logo printing on 150 gm sticker paper			

Table 5. Sample

Sample	Frequency	Percent
staff	30	50.0
Factory owners	10	16.7
Consumers	20	33.3
Total	60	100.0

Table .6. The opinions of faculty members and their differing responses

question	agree		moderate		Not agree		Chi-Square	Sig.
	Frequencies	Percent	Frequencies	Percent	Frequencies	Percent		
Q1-1	26	87	4	13	0	0	16.133**	.000
Q1-2	23	77	7	23	0	0	8.533**	.003
Q1-3	28	93	2	7	0	0	22.533**	.000
Q1-4	23	77	7	23	0	0	8.533**	.003
Q1-5	28	93	2	7	0	0	22.533**	.000
Q1-6	22	73	8	27	0	0	6.533*	.011
Q2-1	23	77	7	23	0	0	8.533**	.003
Q2-2	0	0	7	23	23	77	8.533**	.003
Q2-3	0	0	23	77	7	23	8.533**	.003
Q2-4	0	0	25	83	5	17	13.333**	.000
Q2-5	21	70	9	30	0	0	4.800*	.028

* significant at the 0.05 level

** significant at the 0.01 level

Table 6 illustrates: the agree percentage of faculty members with the structure design with an inclination of 45 degrees of the bottles, function, aesthetics, and the easy of closing and opening the bottle, as ergonomic aspects was laid in the ranging from 73 to 93%. On the other hand, printing bottles, the percentage of disapproval for direct printing on bottles was 17% as the quality of printing. Also, moderate agree percentage was 83% where, 70% was approval for digital printing of logo as sticker.

Table 7. The opinions of the factory owners and their differing responses:

question	agree		moderate		Not agree		Chi-Square	Sig.
	Frequencies	Percent	Frequencies	Percent	Frequencies	Percent		
Q1-1	8	80	1	10	1	10	9.800**	0.007
Q1-2	7	70	2	20	1	10	6.200*	0.045
Q1-3	7	70	2	20	1	10	6.200*	0.045
Q1-4	9	90	1	10	0	0	6.400*	0.011
Q1-5	8	80	1	10	1	10	9.800**	0.007
Q1-6	8	80	1	10	1	10	9.800**	0.007
Q2-1	7	70	2	20	1	10	6.200*	0.045
Q2-2	1	10	2	20	7	70	6.200*	0.045
Q2-3	0.0	0	9	90	1	10	6.400*	0.011
Q2-4	1	10	7	70	2	20	6.200*	0.045
Q2-5	8	80	1	10	1	10	9.800**	0.007

* significant at the 0.05 level

** significant at the 0.01 level

Table 7 illustrates: The Structure design of the bottles for factory owners is inexpensive, and the percentage ranges from 70% to 90%. Also, the extent of their satisfaction with the structure

design of the bottles ranges from 70% -80%, as for printing bottles, the percentage of disapproval for direct printing on bottles was 20% as the quality of printing. Also, moderate agree percentage was 70%., where, 80% was approval for digital printing of logo as sticker.

Table 8. The Consumer opinions and their differing responses

question	agree		moderate		Not agree		Chi-Square	Sig.
	Frequencies	Percent	Frequencies	Percent	Frequencies	Percent		
Q1-1	16	80	4	20	0	0	7.2**	.007
Q1-2	15	75	5	25	0	0	5*	.025
Q1-3	16	80	4	20	0	0	7.2**	.007
Q1-4	15	75	5	25	0	0	5*	.025
Q1-5	15	75	5	25	0	0	5*	.025
Q1-6	17	85	3	15	0	0	9.8**	.002

* significant at the 0.05 level

** significant at the 0.01 level

Table 8 illustrates: the percentage of customer who agree with the Structure design with an inclination of 45 degrees of the bottles, function, aesthetics, and the easy of closing and opening the bottle, as ergonomic aspects, ranging from 75 to 85%.

The difference between the opinions of faculty members, factory owners and consumers. In the first dimension

Question	Chi-Square	Sig.
Q1-1	5.636	0.228
Q1-2	5.116	0.276
Q1-3	7.569	0.109
Q1-4	0.982	0.612
Q1-5	8.635	0.071
Q1-6	6.629	0.157

There are no differences between the responses of faculty members, factory owners and consumers in the first dimension, and this is evident from the table that there is no significance between the different categories of the sample

Fifth (The difference between the opinions of faculty members, factory owners. in the second dimension:

question	Chi-Square	Sig.
Q2-1	3.081	0.214
Q2-2	3.081	0.214
Q2-3	0.833	0.361
Q2-4	3.214	0.200
Q2-5	4.303	0.116

Through the previous tables, it was noticed that the percentage of the sample's acceptance of the 45-angled bottles and the PLA material ranged between 75% and 85%, and the Chi-Square value is a statistical function of the approval response [27].

From the results of Table 5, 6, 7 the fife hypothesis of the research is realized.

4. Conclusion

Applied ergonomic designing aspects on three designs for packaging bottles were successfully presented. The initial design idea come new structure design a 45^{o} inclination angle. In addition, manufacture the ergonomic design with 45^{o} inclination was carried out through 3D printer with ecofriendly and biodegradable polymer as future PLA needed packaging materials.

PLA printed bottles were tested as packaging material by mechanical properties, overall migration test and migrated heavy metal detection. All results are acceptable according to ASTM, ISO, and EC standard methods. The bottles were printed with designed logo four color through direct digital printer or over paper sticker as two commonly using method for prototype production. The printing label properties pointed to nice printing quality according to ISO 12647. Overall, PLA bottles with creative ergonomic structure design are successfully to be ecofriendly and health care packaging materials. In addition, statistical study for academic member, factories owners and customers shown the high degree of approval to design, print and easy use of produced PLA bottles as innovative packaging materials.

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