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Editorial

The APETT Journal aims to provide a broad coverage of subjects relating to engineering. Preference will be given to papers describing original engineering work, or material of specific interest to engineers and those working in related fields, in Trinidad and Tobago (T&T) and the Caribbean region.

This Issue (Volume 48 Number 1) of the Journal includes six (6) articles. The relevance and usefulness of these articles are summarised below.

R.U. Owolabi, M.A. Usman, and **A.J. Kehinde,** "Industrialisation in a Changing Climate: The Role for Process/Chemical Engineers", is concerned with the use of biodiesel for fossil diesel replacement. The achievable reduction in the amount of greenhouse gases (GHG) emission through the use of biodiesel has been found to depend on the feedstocks selection, process technicalities and strategies. The capital intensive nature of the large scale biodiesel production to meet the increasing energy needs resulted to those nations not being able to embrace this noble replacement for fossil fuel. The direction of research and development should therefore rest on a tripod stand of lowering biodiesel cost, minimising GHG emission and ready arable land. To align with the tripartite objectives, this paper conducted an intensive literature search to deepen our chemical and process engineering thinking of the biodiesel plant system design and identification of the optimum biodiesel process technology scale-up in terms of cost, quality, quantity, process safety and environmental considerations, with particular reference to the challenges in Nigeria.

In their paper, "Effect of Particle Size and Particle Loading on Tensile Properties and Thermal Conductivity of Iron Ore Tailings Filled Polypropylene Composites", **M.A Onitiri,** and **S.A. Oladosu**, investigated tensile properties and thermal conductivity of iron ore tailings that were used as particulate filler in polypropylene to produce particle filled plastic composites (PFPCs). Based on particle specimens of simple geometry in a controlled environment, mathematical models including the rule of mixture (such as the parallel model and the series model) were used to predict the thermal conductivity of PFPCs. The theoretical results were validated using the experimental data. It was discovered that the composite with particle loading of 25% gave the highest tensile strength for particle sizes 75 μm and 100 μm while the highest thermal conductivity was experienced at the particle loading with values of 0.376, 0.427 and 0.394 W/m-K for 53, 75, and 100 μm, respectively. The model gave reasonable predictions of the thermal conductivity of the composites for various particle sizes and particle loading considered. The parallel and series model showed poor predictability with increasing particle loading.

R. Murray *et al.*, "Investigation of Cocoa Pod Husk Mechanical Behaviour and the Impact upon Specific Cutting Energy", aim to examine the energy requirement for the cutting of cocoa pod husk. Firstly, a Universal Testing Machine was used to determine the force required and energy absorbed in the tensile testing, compression testing and cutting of the husk. A typical shredding machine was used to determine the specific cutting energy for producing chips of quarter inch length. Lastly, the work examines the impact of cutting speed on specific energy consumption. The results indicated that specific cutting energy increased with cutting speed, with an observed maximum of 1.63 J/g, showing that cutting at slower speeds is preferable, as it leads to lower energy consumption. Moreover, it was found that more energy is required in the cutting of the husk, than in its separation via pure tension. An alternative size reduction process to cutting may be more effective in decreasing the associated energy consumption of comminution.

S. Mohamed *et al.*, "A Compact Urban Aquaponic Irrigation System for the Caribbean Region", present the design and testing of a prototype aquaponic system alongside a conventional soil-based farming system. The aquaponic system consisted of a 946 L fish tank where 20 tilapia (*Oreochromis niloticus*) fishes were reared. The tilapia fishes were fed with a commercial floating fish feed and the fish waste water produced was filtered and the effluent was then used to irrigate the hydroponic beds which comprised of 130 plants. Tests showed that the performance of the aquaponic system was better than that of the conventional farming system in terms of shoot diameter, plant height and the number of leaves present. This was attributable to the developed state of the bacteria colony in the aquaponic system which allowed for the conversion of the ammonia quickly and resulted in a high average nitrate level needed for plant growth. The survival rate of the fishes was 90% and the tilapia fishes experienced an average weight gain of 167.80% during the testing period of two months. The performance of this aquaponic system is encouraging and could be used in an urban setting with the climatic conditions of Trinidad and Tobago.

M. Ramrose and **K.F. Pun**, "DIALux Capabilities with Planning of LED Lighting Solutions: Some Findings in Trinidad and Tobago", investigate the current challenges and issues faced in adopting LED lighting in projects, and show cases how the DIALux system could be utilised for generating viable lighting solutions in Trinidad and Tobago (T&T). This paper reviews the concepts of LED lighting solutions and the factors affecting LED adoption in lighting projects. It then relates the challenges of LED adoption, and explores suitable lighting solutions using DIALux, in projects of both public- and private-sectors in T&T. For exploring the

DIALux capabilities for generating LED lighting solutions, projects of varying nature were selected and then diagnosed with the DIALux system. Compared to traditional lighting, LED lighting has superior qualities in various ways such as being energy efficient, has a long lifespan, durable, and is environmentally friendly. It was found that industry practitioners lacked the knowledge of adopting LED lighting. From the analysis of the selected lighting projects, DIALux could rectify issues in determining the number of lighting, the style of lighting and the installation position of the lighting. Adopting DIALux could generate useful results at the planning stage of lighting projects.

O.B. Owolabi, L.O. Osoba and **S.O. Adeosun.,** "Determining Thermal Characteristics of an Oil-Fired Crucible Furnace Using Clay and Alumina Bricks", explores the results of an experimental study that was intended to determine the thermal characteristics of an oil-fired crucible furnace using clay and alumina bricks. For the study, a refractory with $0.03118m^3$ combustion chamber capacity was used. The bricks analysis was carried out under transient condition that would be appropriate for laboratory and workshop with a capacity to reach 950ºC within 20 minutes for aluminum and nonferrous scrap re-melting. The performance of the furnace was evaluated, and the results showed that the furnace can operate at a heating rate of 49.44°C/min, with a 29.70% efficiency determined, and which was within the efficiency range of conventional furnace. The heat transfer coefficient of $4.48W/m^2K$ was obtained. Alumina bricks used in lining the furnace was attributable to its higher refractoriness. It was found that a better thermal shock was proved than clay bricks from the Comparative analysis simulation using commercial software ANSYS 14.0 towards improved service life and efficiency.

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On behalf of the Association, we gratefully acknowledge all authors who have made this issue possible with their research work. We greatly appreciate the voluntary contributions and unfailing support that our reviewers give to the Journal. Our reviewer panel is composed of academia, scientists, and practising engineers and professionals from industry as listed below:

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Industrialisation in a Changing Climate: The Role for Process/Chemical Engineers

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Abstract: *There are frightening reports by researchers globally about the changing climate, its deleterious effects and the strong need to preserve the world for the future generations. Lengthy lists of research outcomes have attributed the unfortunate situation to the emission of greenhouse gases (GHG) into the atmosphere by virtue of our daily activities. The reclamation of the climatic conditions is thus important. The United Nation, the European Union, science and engineering communities and other stakeholders have brainstormed on many fora and at different times on mitigation strategies. One of such is the replacement of the use of synthetic feedstocks with feedstocks from biological building blocks. Of particular interest in this study is biodiesel for fossil diesel replacement. The achievable reduction in the amount of GHG emission through the use of biodiesel has been found to depend on the feedstocks selection, process technicalities and strategies. The capital intensive nature of the large scale biodiesel production to meet the increasing energy needs resulted to those nations not being able to embrace this noble replacement for fossil fuel. The direction of research and development should therefore rest on a tripod stand of lowering biodiesel cost, minimising GHG emission and ready arable land. To align with the tripartite objectives, this paper conducted an intensive literature search to deepen our chemical and process engineering thinking of the biodiesel plant system design and identification of the optimum biodiesel process technology scale-up in terms of cost, quality, quantity, process safety and environmental considerations, with particular reference to the challenges in Nigeria.*

Keywords: *Greenhouse gases, Biodiesel, Biological building blocks, climate change, chemical and process engineering*

1. Introduction

Human activities have considerably tampered with the natural ecosystem in the search for improved lifestyle through mass production of daily needs, general industrialisation and sound transportation systems. The aftermath of these is gradual pollution of the atmosphere, water bodies and landed regions. Some of the pollutants are greenhouse gases (GHG) such as CO_2, CH_4, NO_X (Hansen et al. 2007). Greenhouse gases envelope the atmosphere thus preventing heat from getting into the outer space giving rise to global warming (Steen, 2001; Flint, 2011). The implications of the pollution effects have over the years drawn the attention of inter-disciplinary researchers and policy makers. For instance, a recent report by Ramakrishnan (2015) shows that the global average temperature has risen by 1 ^oC. A further projection of 2.5-10.4 ^oC rise was also estimated for the next century (IPCC, 2014).

In another study, Ahmad et al. (2011), reported a strong likelihood of about one million species going extinction with loss of hundreds of millions of people if there is more than a 2^{o}C rise in the average global temperature. The later statement may come to reality based on model estimates and future projections of the greenhouse emissions. This is further supported with the fact that the warmest years so far were recent i.e 1998, 2005, 2009, 2010, 2013, 2014, 2015 and 2016 with year 2016 taking the lead. For CO_2, approximately 4.1 billion metric tons may be released into the atmosphere from 2007 to 2020. In addition, a further estimate of 8.6 billion metric tons may be released into the atmosphere for the next fifteen years (EIA, 2010). Methane release constitutes 15% of the greenhouse gas effects with sources basically from fossil fuel, petroleum industries, burning of biomass, decomposition of organic matters and has heat absorbing potentials 84 times than CO_2 (Ramakrishnan, 2015; Ramanathan, 1997; Hiroki, 2015). The oxides of nitrogen also contribute to 5% of the greenhouse gas effects with source from fertilisers application for large scale farming with heat trapping effects 300 times than CO_2 (Ramakrishnan, 2015).

In another scenario, situations such as melting of the ice bergs, rising sea level, and volcanic eruption were identified as further consequential effects of the changing climate (Ramakrishnan,2015). In fact, the rising sea level has been associated with the high frequency of storm, cyclone and flood (Gschrey and Schwarz, 2009). This particularly increases the chances of flooding in human dominated regions (Tirado et al., 2010). In other reports, climate change and variability has been predicted to intensify and enlongate droughts period particularly in the tropics and sub-tropics (Trenberth et al., 2007). There is also evidence of ocean acidification due to increased atmospheric CO_2 (The Royal Society, 2005).

Going by GHG emission of some countries, some researchers reported extensively on the contribution of Greece – a developing nation in terms of release of GHG as follows - 79.9 % of CO_2, 8.1% CH_4 , 8.2% NO_X and others mostly from combustion of fossil fuel, production and transportation. This led to the summer periods becoming hotter and winter periods becoming colder in Greece (Feidas et al., 2004) as well as increase in numbers of tropical days in a year and dessert encroachment. In the case of United State of America (USA) - a developed nation, CO_2 release from both industrial and transportation activities was estimated to be 9.9 billion US tonnes of CO_2 on an annual basis (EIA, 2010). These frightening illustriations call for stringent policies on social, economic, environmental and technical sustainable measures. The good side is that the gravity of the GHG effects depends on their concentrations in a locality (Lacis et al. 2010). A strong call for the optimal presence of the GHG is therefore a must if we are to preserve the globe for future generations.

In 1988, the United Nations (UN) established the Intergovernmental Panel on Climate Change (IPPC) where fossil fuel received overwhelming responsibility for climate change. In this regard, if fossil fuel subsidies can be phased out, it was projected that about 2.6 giga tonnes of CO_2 can be avoided by the year 2035 (Wang, 2015). The Pittsburg G-20 summit met on fuel subsidy removal in 2009 to limit global warming and promote social justice but with little success (Wang, 2015). The United Nations promoted the Kyoto Protocol in 1997 which aimed at reducing greenhouse gases such as CO_2, CH_4, SO_2, NO_2 by 5.2% on the basis of the emission in 1990, and more than 170 countries ratified the protocol (Gutierrez et al., 2008). The European Union (EU) targeted up to maximum of 30 % reduction in CO_2 by the year 2020. The serious campaign for bio-based products and its utilisation has been identified as a strategy to meet the target. Specifically, bioethanol and biodiesel to reach production capacity of 39.3 million tonnes and 8.3 million tonnes respectively (FAPRI, 2008; OECD/FAO, 2008). The details of other concerted efforts geared at mitigating the changing climate such as the Lisbon treaty etc that can be found in a study of Carvalho (2012).

In light of the concerted efforts and mounting pressures towards combating climate change, chemical engineering researchers have posited varying options ranging from decarbonisation of electricity production (Kouloumpis et al., 2015), carbon capture and storage, turning captured carbon into useful products (Ceullar-Franca and Azapagic, 2015), development of shale gas (Newell and Raimi, 2014) and replacement of fossil fuel with biodiesel (Folasegun et al., 2014; Yordanov et al., 2013; Kang et al., 2013; Owolabi et al., 2013; Owolabi et al., 2011; Owolabi et al., 2012; Porte et al., 2010; Shu et al., 2010; Kasendo et al., 2009; Singh and Singh, 2009; Lapuerta et al., 2009; Canoira et al., 2008; Canoira et al., 2007; Kumar et al., 2007; Canoira et al., 2006). The gradual replacement of fossil with biodiesel seems to gain wider acceptance which is also the direction of this study. Furthermore, between 1975 and 2005, the rate of global energy usage doubled (Bueno et al., 2009). On this consideration again, there is urgent need for additional source of energy. Noteworthy is that, the wide acceptance of biodiesel is not unconnected with its life cyle reports. Feedstocks must be grown, transported, processed and utilised (Pena, 2008). The cummulative emmissions therein give a positive impart of the biodiesel on the nation's GHG emission. Reflections on Table 1 show in practical terms profile in emission either when B20 (20 % biodiesel blend with 80% petroel diesel) or B100 (100% biodiesel) burns in engines.

The United States of America, Brazil and some of the EU countries have invested heavily in the biodiesel sector (Cardoso et al. 2017) with no African country with similar foresight (see Table 2).

The current production of global biodiesel is about 30.1 billion litres. The United States of America alone produced 4.8 billion litres which accounted for 15.9% of the global biodiesel production closely followed by Brazil with a capacity of 3.9 billion litres, 12.9% of the global production and other EU nations with a collective capacity of 16.2 billion litres, accounted for about 53.8% of global production (REPN, 2016). Alcohol from starchy crops and oil from oily seeds or animal fats are the major feedstocks for the biodiesel production. The two heavy biodiesel producers utilise ethanol and soy bean oil as major feedstocks (Cardoso et al. 2017; Campbell, 2000) though research is currently been stimulated towards utilisation of other raw materials in Brazil while the rapeseed oil also called canola oil is utilised as major feedstocks in the EU countries (Ajanovic, 2011).

Table 1. Summary of Percent Change in Emissions for Recent Engine Dynamometer Studies of Biodiesel

Biodiesel (%)	Emissions				References
	NO_X	Hydrocarbon	CO	Particulate Matter	
100 Rape seed methyl ester	≈ 0	----	----	-20	McGill et al. (2003)
30 Rape seed methyl ester	1.7	0	-9.4	-24	Aakko et al. (2000)
20 Soya oil methyl ester	-10.3	-20	-38	-2.9	Frank et al. (2004)
20 Waste grease	0.3	-7.0	-25	-20	Souligny et al. (2004)
20 Animal fat	-1.5	-13	-17	-22	Souligny et al. (2004)

Table 2. Biodiesel Production Capacities of Producing Countries as at 2016

S/N	Country	Production Capacity (in Billion litres)
1	United States of America	5.5
2	Brazil	3.8
3	Germany	3.0
4	Indonesia	3.0
5	Argentina	3.0
6	France	1.5
7	Thailand	1.4
8	Spain	1.1
9	Belgium	0.5
10	Columbia	0.5
11	Canada	0.4
12	Others	0.3

Source: Energy and Environmental services (2016) (https://www.statista.com)

Table 3. United States of America / Nigeria Parameters for Biodiesel Production

Parameters	**United States of America**	**Nigeria**	**Reference**
Oil Feedstock for Biodiesel	Soy Oil	Castor Oil (Planned)	Cardoso et al., 2017; Campbell, 2000
Population	325.7 million	186 million	http://www.mylifeelsewhere.com/country-size-comparison/united-states/nigeria
Land mass	9,833,517 square metre	923,768 square metre	www.mylifeelsewhere.com/country-size-comparison/united-states/nigeria
Agricultural Land	174.45 million hectares	30.5 million hectares	http://www.nationmaster.com/country-info/compare/Nigeria/United-States/Agriculture
Land mass for growing Biodiesel oil feedstock	77.5 million hectares (2009)	None	https://www.ers.usda.gov/topics/crops/soybeans-oil-crops/background/
Gross Domestic Product	19.42 trillion US dollars	405.1 billion US dollars (2016)	https://www.investopedia.com/articles/investing/022415/worlds-top-10-economies.asp
Biodiesel production capacity	5.5 billion litres (2016)	None	Energy and Environmental services, 2016

The use of the feedstocks seems to be dictated by the geographical differences in the regions. The shortcoming of these scenarios is the costly aspect of the biodiesel compared to fuel from fossil origin which is another direction of this study. The estimated cost of biodiesel ranges from \$1.50 to \$2.50 per gallon depending on the feedstocks and method of production while that of petroleum-based diesel ranges from \$0.20 to \$0.82 per gallon. Since the United States of America has recorded progressive gowth in biodiesel production in past years, Table 3 shows some relevant and recent parameters of the United States with respect to degree of success of biodiesel production which could serve as basis or template for other countries especially African countries to plan ahead. The drive for the production and utilisation of biofuels by some nations is due to their wide applications.

For instance, transportation to promote domestic energy security, stimulate economic development and reduce emissions of GHG, as well as alternative markets and opportunities for agricultural products such as oilseeds and diversification of energy sources, especially renewable energy; and the carbon credit market (Popp et al., 2016; Finco, 2012; Nogueira, 2011). African nations again seem lost in all of these visions and directions whose results aim at societal transformation. This theoretical study therefore focuses on the scale up of a low cost biodiesl production system that will be technically feasible, economically viable, environmentally friendly, materially accessible and tolerant to national policy using Nigeria as a case study.

2. Why Is Biodiesel Expensive?

Table 4 contains the most recent price reports of both fossil fuel diesel and biodiesel in the United States. Comparatiively, biodiesel is expensive. Therefore, the campaign for the use of biodiesel must come with attractive price or price with insignificant differentials with fossil diesel to ensure reasonable shift from the use of fossil diesel to biodiesel. The significant differential in price report is as a result of number of reasons which is the center of this study. Firstly, it takes millions of years for the formation of fossil oil (Bhaskara, 1990). The gradual effects of heat, temperature, pressure and microbial activities on materials of organic origin slowly degrade the carbon-carbon bond in them to ease the formation of fossil oil.

In the case of biodiesel, the degradation of the bonds is induced and almost instantaneous. This therefore seems to bring the future near. Ordinarily, such a process is expected to be costly.

Table 4. United States of America Average Retail Price for Janaury, 2018

Fuel Type	October 2017 ($)/gallon)	January 2018 ($)/gallon	Change in price ($)/gallon
Gasoline	2.49	2.50	0.01
Diesel	2.76	2.96	0.20
Biodiesel (B20)	2.68	2.84	0.16
Bidiesel (B99/100)	3.38	3.48	0.10

Source: Abstracted from U.S Department of Energy (2018)

Table 5. Feedstocks of Biodiesel in Different Countries

S/N	Country	Source of Biodiesel
1.	United States of America	Soya Bean (Mustard is under study)
2.	Brazil	Soya Bean
3.	Europe	Rape seed, Sunflower oil
4.	Spain	Linseed and Olive oil
5.	France	Sunflower oil
6.	Italy	Sunflower
7.	Ireland	Animal fat, Beef tallow
8.	Indonesia	Palm oil
9.	Malaysia	Palm oil
10.	Australia	Animal fat, Beef tallow, rape seed
11.	China	Guanpi
12.	Germany	Rape seed
13.	Canada	Vegetable oil/Animal fat
14.	India	Jatropha

Source: Abstracted from Divya and Tyagi (2006)

Biodiesel production needs intensive human inputs, not only in terms of skilled and technical personels but also the labour that will go through the rigours of agricultural intensification, clearing, harvesting on a continuous basis within a short period of time. This also calls for heavy financial inputs. The high cost of the feedstocks and the system or structure to ensure their constant supply is another aspect of the cost (Phan and Phan, 2008; Zhang et al., 2003; Berrios et al., 2011). Biodiesel can change with time because of its bio-sourced components. It therefore needs to be constantly agitated and conditioned which will further compound the final production cost of biodiesel.

The full capital cost of a feedstock capacity of 70,000 tonne per year is likely to cost $20-30 million (Duncan, 2003) where oil alone accounts for about 70 % (Dias et al., 2013). For rape seed for instance, in 2006, its average productivity in the EU was 2,970 kg per hectare. The Total production of the seed in EU that same year was 15.8 billion tonnes. Of these, 1 Kg of the seed can generate 387g of biodiesel which implies that 1 hectare of the oil seed produces 1,150 kg of biodiesel (Carlsen et al., 2006). From another view, the energy requirement in terms of the process steps for biodiesel production is large and expenive (Leung et al., 2010). For instance, the energy requirement for the agitation, extraction, trans-esterification and separation. The cost of powering the biodiesel production plant with fuel of renewable source is also one of the directions of this study. Having a more efficient biodiesel production process to overcome the afore-mentioned biodiesel cost implication is central to this study.

3. Feedstocks for Biodiesel Production in Nigeria

Biodiesel feedstocks selection depends on the accessibility, cost, national policy, and food security in the locality (Knoth et al., 2009). The quality, functionality and production steps of biodiesel production begin with the feedstocks. Table 5 shows oily seeds utilised by biodiesel producing countries. For the Nigeria soil and climate, castor oil - an inedible oil obtained from castor plants seems favourable as it thrives around Nigerian bushes without care (Bateni and Karimi, 2015). This is unlike other crops used by other countries of the world. Other non-edible oils not listed are Jatropha oil, Karanjaor Pongamia oil, Neem oil, Jojoba oil, Cottonseed oil, Linseed oil, Mahua oil, Deccan hemp oil, Kusum oil, Orange oil, and Rubber seed oil (Vasudevan and Briggs, 2008; Hossain and Davies, 2010).

In other reports, researchers observed that the castor oil is soluble in alcohol and its transformation therefore does not require much heat and consequent energy expenditure unlike other vegetable oil (Kiany et al., 2010; Costa, 2004). Again, the castor oil does not require pre-treatment since it contains insignificant amounts of phospho-lipids. These sterling qualities give castor oil an edge over others. This observed behaviour of castor oil is due to the predominance of ricinoleic acid, which possesses an unsaturated bond (Perdomo et al., 2013).

Ricinoleic acid (12-hydroxy-9-cis-octadecenoicacid) belongs to the group of hydroxylacids and is characterised by a high molar mass (298.461 g mol^{-1}) and low melting point (5.5°C). The hydroxylated fatty acids of ricinoleic acid incastor oil have been hypothesised to make the oil better perform as lubricity enhancer compared with toother common vegetable oil esters, Ramezani (2010). Cultivation of the castor plant under conducive climate was found to boost the seed yield to 4-5 t/ha, leading to promising oil productivity. The total arable land in the EU is 109.4 million hectares. About 6.1 million hectares was used for rape seed cultivation in 2006 and was augmented to 10.2 million acres in 2010. There may be some challenges with land acquisation in Nigeria ranging from socio-cultural to get the needed volume of oil for biodiesel production. Efforts to overcome these challenges will be an opportunity to combat the changing climate.

4. Synthesis of Biodiesel

Srivathsan et al. (2007) reported the feasibility of direct usage of raw oil as biodiesel feedstock by blending with fossil diesel. The blending process requires less equipment cost but the raw oil has low volatility and high viscosity. These limitations may result in knocking engines or create related technical issues (Perkins et al., 1991; Pestes and Stanislao, 1984). For long term usage and storage, raw oil use is also associated with acid contamination, free fatty acid formation resulting in gum formation by oxidation and polymerisation of the oil and carbon deposition (Srivathsan et al., 2007). Raw oil therefore needs to be pre processed to acquire fuel properties close to that of fossil fuels. Pyrolysis or cracking, micro-emulsification and trans-esterification are the processing techniques known (Ma and Hanna, 1999). Trans-esterification has been widely accepted and utilised (see Figure 1) for biodiesel production (Folasegun et al., 2014; Yordanov et al., 2013; Kang et al., 2013; Owolabi et al., 2013; Owolabi et al., 2011; Porte et al., 2010; Shu et al. 2010; Kasendo et al. 2009; Singh and Singh, 2009; Lapuerta et al., 2009; Canoiraet al. 2008; Canoira et al., 2007; Kumar et al., 2007; Canoira et al., 2006).

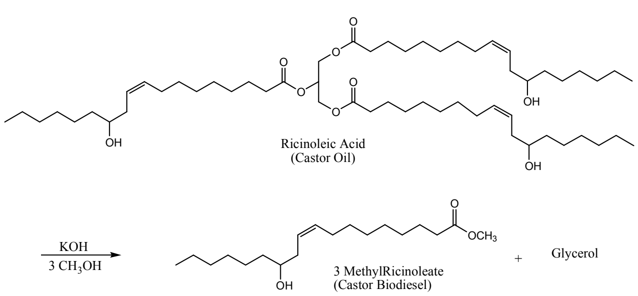

Figure 1. Catalytic methyltrans-esterification of castor oil

Trans-esterification is the catalytic chemical process that transforms the oil feedstocks into biodiesel usually in the presence of alcohol either methanol or ethanol. Through this, the process lowers the viscosity of triglycerides (Urioste, 2004). The choice of methanol or ethanol depends on cost, availability and locality. We consider ethanol as a better option in terms of cost, availability and renewability unlike methanol that is only sourced from petrochemicals industry.

On the other hand, methanol is also considered better as it does not form azeotropes unlike ethanol. Recent technology have shown that the trans-estrification can be assisted by micro wave or ultrasound. Micro wave assisted process has commercial scale-up problem because of high operating conditions involved and safety aspect (Yoni and Ahron, 2008).

For the trans-esterification, biodiesel can be produced through three processes namely; base-catalysed transesterification of the feedstock with alcohol, acid-catalysed esterification with methanol and conversion of the oilto fatty acids , alkyl esters consecutively through acid catalysation (NBB, 2007). For economic reasons, the base catalysed system (see Figure 1) is commonly used. The energy requirement for the trans-esterification is also key. Selection of evolving renewable energy sources must be done to avoid further GHG emission. Bio gas has been tipped in this study to meet the trans-esterification process energy demand. Nonetheless, solar collectors, geothermal wells, wind turbine are competitive means of energy providers. Their application depends on economical challenges and geographical locations of various countries.

5. Catalysts for Trans-esterification Reaction

Trans-esterification reactions are performed under catalysed conditions due to its slow reaction rate (Rutz and Janseen, 2007). This is due to the difference in the polarity of the feedstocks resulting in mass transfer limitations or resistance. Aside rate effect, catalyst also progresses reactions at milder conditions. Homogeneous and heterogeneous acids and bases as catalysts found intense application in biodiesel production. The commonly used homogeneous catalyst is H_2SO_4 (Leung et al., 2010; Meher et al., 2006; Barnwal and Sharma, 2005; Fukuda et al., 2001, and Ma et al.,1999), while commonly used homogeneous bases are lyes such as NaOH, KOH (Owolabi et al., 2011).

Lipases enzymes catalysts such as *Nozozyme 435, Candida rugosa, Rhizopusoryzae, Geotrichum sp. and Penicillium expansum* lipase catalyst have also received application in biodiesel production (Yan et al, 2011; Lee et al., 2011). Base catalysts are corrosive and also prone to a side reactions with bye products that are expensive to separate (Wen et al., 2010; Song et al., 2011). The homogeneous acid catalysts are hydrophilic and operate at slower relative rate (Nasir et al., 2013). Traits exhibited by homogeneous catalysts may jeopardise chances of low cost biodiesel production especially at industrial level. They are also not compatible for all kinds of oil. To the best of our knowledge, the industrial scale application of lipase catalysed biodiesel production is still at the infancy stage. Some current studies have focused on heterogeneous catalysts with some degree of success. For instance, Park et al. (2010) used WO_3/ZrO_2 for free fatty acid (FFA) conversion to biodiesel and the yield was approximately 93%, Yan et al. (2009) used a number of heterogeneous zinc and lanthanum mixed oxides for biodiesel production of unrefined or waste oils and obtained a yield of 96 %. For biodiesel production from soybean oil, Xie and Li (2006) used Alumina-supported potassiumiodide and the yield of 96% at 773 K in air was achieved.

Additionally, heterogeneous catalyst does not lead to side reactions. Table 6 further shows summary of catalyst previously used and their optimum operating conditions. Non-catalytic trans-estrification at supercritical conditions have also been reported but with varied degree of success (Kusdiana and Saka, 2004; Tan et al., 2009; Ilham and Saka, 2010). The method reduces reaction time but requires harsh thermodynamic conditions (Nasir, et al., 2013) thereby putting the industrial scale production at risk. The future focus is to synthesise, characterise and test run the functionality of the new set of catalysts from both plants and animal sources namely; orange peels, banana peels, groundnut shell and egg shell for possibilities of improved catalytic actions over the previously used catalysts and generation of functionalised catalysts.

6. Process Parameters and Optimisation for Biodiesel Production

A lot of studies have been done on the effects of process parameters on the quality and yield of biodiesel. Some of the essential parameters are the reaction time, temperature, catalyst concentration, agitation speed and reacting species molar ratio (Cavalcante et al., 2010; Da Silva et al., 2006; De Oliveira et al., 2005; Jeong and Park, 2009; Ramezani et al., 2010). Most studies were operated at atmospheric pressure (see Table 6). A further commendable attempt made by previous researchers was the optimisation of the entire process to determine conditions of best interest in terms of yield using the response surface methodology (De Oliveira et al., 2005; Da Silva et al., 2006; Ramezani et al., 2010; Dias et al., 2013;Usman et al., 2017). Varying regression models were generated in terms of process parameters for the prediction of yield (Eq.1) where Y is the predicted response, b_o is a constant coefficient, b_i is a linear coefficient, b_{ii} is the quadratic equation, b_{ij} is an interaction coefficient, and X_i and X_j are the coded values of the process variables.

$$Y = b_o + \sum_{i=1}^{n} b_i X_i + \sum_{i=1}^{n} b_{ii} X_{ii} + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} b_{ij} X_i X_j \quad (1)$$

This aspect assists in capturing the likelihood of occurrences with changes in operating parameters at short notice, at no cost in a consistently safe manner. However, kinetic and other thermodynamic consideration which could serve as limitations to chemical reaction were not captured which this study identifies as a gap to fill. There is a possibility of operating at lesser yield as against the predictions of the regression model and still be optimum.

7. Trans-esterification Kinetic Modeling

A lot of studies have been carried out on biodiesel production with special emphasis on its kinetics (Narvaez et al., 2007; Nourreddini and Zhu, 1997; Kusdiana and Saka, 2001; Minami and Saka,2006; Joelianingsih et al., 2008; Freedman et al., 1986). The overall trans-esterification reaction for biodiesel production is represented by Eq (2), where TG stands for Triglyceride and GL stands for Glycerol.

$$TG + 3CH_3OH \leftrightarrow 3RCOOHCH_3 + GL \quad (2)$$

The reaction mechanisms shown in Eq. (3-5) have been widely accepted for the trans-esterification process (Narvaez et al., 2007; Nourreddini and Zhu, 1997; Kusdiana and Saka, 2001; Minami and Saka, 2006; Joelianingsih et al., 2008; Freedman et al., 1986).

$$TG) + 3CH_3OH \leftrightarrow R_1COOHCH_3 + DL \quad (3)$$

$$DL + 3CH_3OH \leftrightarrow R_2COOHCH_3 + ML \quad (4)$$

$$ML + 3CH_3OH \leftrightarrow R_3COOHCH_3 + GL \quad (5)$$

Where,
TG = Triglyceride
DL = Diglyceride
ML = Monoglyceride
GL = Glycerol

Generally, Kinetics studies and modeling are to identify rate parameters for reactor design. For the trans-esterification reaction, past data generated were from reactors operated under laboratory conditions (see Table 7). Therefore, a detailed kinetic studies for a scaled up reactor design and control system is thus essential for industrial biodiesel production.

Table 6. Reported parameters for the catalytic trans-esterification reaction

S/N	Catalyst	Temperature (ºC)	Pressure (Bar)	Conversion (%)	Reference
1	NaOH	60	1	94.3	Narvaez et al., 2007
2	H_2SO_4	130	1	90	Wang et al., 2006
3	KOH/Al_2O_3	70	1	91.7	Noiroj et al., 2009
4	DTPA/Clay	70	17	94	Bokade and Yadav, 2009
5.	K-Carrageenan	30	1	99	Jegannathan et al.,2011
6.	Super critical methanol	350	40	95	Song et al., 2008
7.	Lipase	45	1	95	Seri et al., 2008

Table 7. Trans-esterification Reaction in Different Reactors

S/N	Reactor Type	Reaction Conditions	Reference
1	Membrane reactor	Canola oil, 60 -70 ºC, 6 hrs, H_2SO_4 Catalyst (0.5-0.6wt)	Dube et al. (2007)
2	Double column reactor	Refined palm oil, 250-290ºC, Super heated methanol at 0.1Mpa, 230-290ºC, 4g/mins	Joelianingsih et al. (2008)
3	Jet flow stirred reactor	Blend of soy bean oil and Sunflower oil, 90 ^{0}C,1 hr, Catalyst 1 wt%	Reyes et al. (2010)
4	Packed bed reactor	Soy bean oil, Room temperature, Ultrasoniification	Hama et al. (2007)

8. Low-cost Biodiesel Commercial Process Technology and Biodiesel Characterisation and Analysis

For the production of biodiesel, the underlisted approaches have been considered for integration into the process design for large-scale biodiesel production at low cost. These include:

- Use of castor oil feedstock
- Fermentation of castor seed residue for ethanol production
- Simultaneous extraction (Hexane) and trans-esterification
- Optimisation of reaction parameters
- Optimisation of feedstocks
- Process Integration
- Catalyst from biomass
- Ultrasonic device for mass transfer elimination
- Application of co-solvents
- Effective means of powering of the biodiesel plant

The feedstocks used during biodiesel production determines the end properties of the biodiesel. Some of these properties are:

1) Flash point: The flashpoint of a fuel is the temperature at which the vapour above the fuel becomes flammable. The flash point of fossil diesels is between 50 and 80°C while that of biodiesel is 160°C. This implies that the fire hazard associated with transportation, storage and usage of biodiesel is much less compared to fossil
2) Cetane number: This indicates fuels readiness to auto ignite after it has been injected into the diesel engine. Diesel fuels from the refineries are with cetane numbers between 40 and 50. Again, for biodiesel, cetane number is usually between between 46 and 60 depending on the feedstock used. This implies that fuel with high values shortens the ignition delay in the engine and consequently improves the combustion characteristics (Biodiesel Education, 2006).
3) Cold temperature properties: These are to measure the behaviour of the fuel under low ambient temperatures. One of these is the cloud point which denotes the temperature at which the first visible crystals are formed. Another is the pour point which is the lowest temperature to which the sample may be cooled while still retaining its fluidity.
4) Viscosity: This is the resistance to flow of oil. Ease of starting depends on viscosity. Glycerin contamination may cause biodiesel viscosity to increase (Divya and Tyagy, 2006). Production of biodiesel with much reduced viscosity and cloud point can be found in the patent of Nourreddini (1997).

Table 8 shows the fuel properties of biodiesel from various sources, whereas Table 9 depicts a comparison of heat combustion and specific gravity of diesel fuel versus selected biodiesel fuels.

Table 8. Fuel Properties of Biodiesel from Various Sources

Fuel	Specific Gravity	Flash Point ºC	Pour Point ºC	Cloud Point ºC	Viscosity @ 40ºC mm^2/s	Cetane Index
[1]Petroleum Diesel	0.853	74	-16	-12	2.847	-
[2]Palm Oil Biodiesel	0.883	167	2	6	4.839	-
[3]Rape Seed Biodiesel	0.876	124	-2	-10	6.170	-
[4]Canola Biodiesel	0.878	177	-1	-6	4.892	-
[5]Jatropha Biodiesel	0.880	170	-	-	5.650 (sct)	50.00
[6]Waste Cooking Oil	0.858	-	7	10	1.890	10.96
[7]Biodiesel Standard	0.875-0.9	100	-	-	5.000	49.00

Sources: [1-4] Alamu et al. (2008); [5] Reddy and Ramesh (2005); [6]Sarin et al. (2007); [7]NBB (2007)

Table 9. Heat of Combustion and Specific Gravity of Diesel Fuel versus Selected Vegetable Biodiesel Fuel

Fuel Type	Heat of Combustion (kj/kg)	Specific Gravity
Diesel Fuel	43350	0.815
Sun Flower Biodiesel	40579	0.878
Cotton Seed Biodiesel	40580	0.874
Soya Bean Biodiesl	39760	0.872
Rape Seed Biodiesel	37620	0.914
PawpawBiodiesel	45342	0.867
Waste Cooking Oil	45479	0.858

Source: Abstracted from Owolabi et al. (2011)

Quality standards for the commercial applications of fuel depend on its quality. Standards vary slightly from one country to the other and must be strictly adhered to. The standards serve as guidelines for efficient production process, guarantee customers that they are buying high-quality fuels and provide the authorities with approved tools for the assessment of safety risks and environmental pollution. As earlier said, the nature of the feedstocks and their modifications count in this regard. Numerous standards are on ground, such as the EN 14214 in the European Union and the ASTM D 6751 in the USA.

9. Conclusion

Chemical and process engineers are the core drivers of industrialisation. The changing climate which has become a threat to human life is a product of the industrilisation. This scenario poses a great challenge to Chemical and Process Engineers. Identified solution from this study is the embracement of biological materials and building blocks as feedstocks for various industrial products. Special emphasis was given to biodiesel production in this study to ensure a low-cost and yet technically feasible industrial production of biodiesel as a gradual replacement for the fossil diesel.

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Effect of Particle Size and Particle Loading on the Tensile Properties and Thermal Conductivity of Iron Ore Tailings Filled Polypropylene Composites

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Abstract: *Iron ore tailings which is the waste produced during the beneficiation of iron ore was used as particulate filler in polypropylene to produce particle filled plastic composites (PFPCs). Particle sizes of approximately 53, 75 and 100 µm and particle loading of 0 to 30 vol. % were considered. Tensile and thermal conductivity tests were conducted on the fabricated PFPCs using specimens of simple geometry in a controlled environment. Mathematical models (developed by Bruggeman, De Loor, and Nan et al.) including the rule of mixture, also known as the parallel model and the series model, were used to predict the thermal conductivity of PFPCs. The theoretical results were validated using the experimental data. It was discovered that the composite with particle loading of 25 % gave the highest tensile strength for particle sizes 75 µm and 100 µm while the highest thermal conductivity was experienced at the 30 vol. % particle loading with values of 0.376, 0.427 and 0.394 W/m-K for 53, 75, and 100 µm, respectively. The model proposed by Bruggeman and De Loor gave reasonable predictions of the thermal conductivity of the composites for all the particle sizes and particle loading considered with the least variation of 0.10 % and 0.15 % recorded for 75 µm particle size inclusions, respectively. The parallel and series model showed poor predictability with increasing particle loading.*

Keywords: *Composites, Iron ore tailings, Particle loading, Particle sizes, Polypropylene, Tensile, Thermal conductivity*

1. Introduction

Particle filled plastic composites (PFPCs) are plastics to which fillers have been added to modify or improve the properties of the plastic and/or replace some of the polymer volume with a less expensive material. Common fillers include wood flour (finely powdered sawdust), silica flour, sand, glass, clay, talc, and limestone. (Callister, 1997; Koshal, 1993). Among the challenges which PRPCs present is the complexity of their mechanical, chemical and thermal behavior. According to McCarthy and Wiggeraad (2001), this makes it difficult to predict performance analytically and hence leads to conservative designs and extensive test programs. Adedayo and Onitiri (2012) posited that the yield and tensile strength improved with reduced and increased particle size, respectively. The latter was found to be contrary to findings by Nakamura et al. (1992) on the tensile properties of epoxy resin filled with angular-shaped silica, where it was observed that tensile strength reduces with decreased particle size. This was attributed to non-homogeneity in composition of the fillers used and not the shape of the particulate fillers.

In another study by Zhang et al. (2011) on the tensile properties of Al_2O_s/high density polypropylene composites, it was discovered that the tensile properties improved with decreased particle size. The highest increment in tensile strength by 12 % was recorded at 30 vol. % inclusion of Al_2O_s. Research conducted by Khalaf (2015) on the effect of fibre glass, $CaCO_3$ and palm leaf lignocellulose (LC) filler on the tensile properties of high density polyethylene (HDPE) shows that yield strength reduced with increased particle loading for all the fillers considered. The LC filled HDPE composites has the highest yield strength for all the particle loadings considered except at 5 wt. % where yield strength of approximately 24.5 MPa and 25 MPa for LC and $CaCO_3$ inclusions, respectively, were recorded.

In the work by Droval et al. (2006) on the effect of boron nitride, talc, aluminum nitride and aluminum oxide particles, and their effects on thermal properties of polystyrene, the Lewis and Nielson, Cheng and Vachon, Agari and Uno models were used to predict the effect of particle loading on thermal conductivity of the composites. It was discovered that the models gave correct prediction of thermal conductivity with boron nitride showing an exponential increase of over 20 vol. % filler. Kumlutas et al. (2003) conducted a numerical investigation into the effect of particle loading on the effective thermal conductivity of aluminum filled high-density polyethylene composites. The results gotten were validated using experimental data and the existing theoretical and empirical models. It was found that reasonable predictions of the numerical results were made by the experimental, theoretical and empirical models at particle loading below 10 %.

Ebadi-Dehaghani et al. (2014) and Ebadi-Dehaghani et al. (2012) worked on the thermal conductivity of polypropylene filled with ZnO and $CaCO_3$ nanoparticles at particle loading of 5 to 15 wt. %. Part of their findings is presented in Figure 1 which is a comparison of the effect of the fillers on the thermal conductivity of the polypropylene composite. It could be seen that the thermal conductivity increased with an increase in the nanoparticle concentration up to 64% and 82% for $CaCO_3$ and ZnO, respectively. The increases in thermal conductivity for both nanoparticles were found to be higher than that reported by Frormann et al. (2008) for PCNF filled PP composites. The experimental data were also used to validate theoretical results obtained from the other Parallel and Series models advocated by Bruggeman (1935), De Loor (1956), and Nan et al. (2004). It was discovered that the Bruggeman (1935), and De Loor (1956) models gave a reasonable prediction for PP/ZnO and PP/$CaCO_3$ composites at particle inclusion lower than 10 wt. %. It was observed that Nan et al. (2004) model gave a better prediction for PP/$CaCO_3$ composites up to 15 wt. % inclusions.

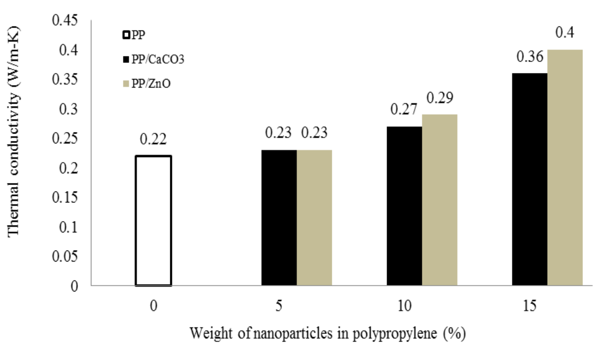


Figure 1. Comparison of the effect of nanoparticles on the thermal conductivity of polypropylene
Sources: Ebadi-Dehaghani et al. (2012, 2014)

In a related work by Onitiri and Akinlabi (2016) on the effect of iron ore tailings particle sizes 150, 212 and 300 μm at inclusions of 5 to 30 vol. % on the thermal conductivity of epoxy, it was discovered that thermal conductivity of epoxy improved with reduced particle size and increased loading for 150 and 212 μm particle fillers.

This present work focuses on the use of iron ore tailings, which are dumped as waste at the iron ore mines, as particulate fillers in polypropylene for relevant structural and thermal applications. Iron ore tailings produced during the mining process of iron ore constitutes a major health and environmental challenge because it could cause severe air and water pollution including land slide. This research looks at the possibility of putting this waste into viable use as fillers in polypropylene (PP) to produced particle filled plastic composites. PP which is one of the most widely used plastics exhibits special qualities compared to other polyolefins, namely; low density (about 0.90 g/cm^3), high melting temperature, chemical inertness, high versatility in achieving required structural design and mechanical properties, diverse morphological structures through the addition of fillers and reinforcing agents. PP and its composites are major materials of choice in the fabrics, packaging, consumer goods, automotive, medical, and other industrial applications.

The composites will be fabricated using the compo-indirect squeeze process developed by Onitiri and Adedayo (2015) in their work on the compressive properties of iron ore tailings filled polypropylene composites. The effect of particle loading and particle size on the tensile and thermal conductivity properties of iron ore tailings filled polypropylene composites will be quantified by conducting tensile and thermal conductivity tests, respectively, on the fabricated PFPCs for possible structural and thermal applications using specimens of simple geometry.

Available mathematical models in literature will also be used to determine the theoretical thermal conductivity of the PFPCs while results obtained will be validated using the experimental data from the thermal conductivity tests. The validation of the theoretical data with the empirical data would provide relevant information on the implication of adopting the models for prediction of the thermal behavior of the composite for relevant thermal applications. The ability to predict the thermal properties of the PFPC, theoretically, would save valuable time and cost that could be incurred from repeated and extensive experimentations.

2. Theory

Various theoretical models have been proposed to predict the thermal conductivity of two-phase composites. Some of the mathematical models developed include Bruggeman's (1935) model shown in Equation (1) below;

$$K_c = \frac{K_m}{(1-\phi_f)} \tag{1}$$

where K_c is thermal conductivity of composite, K_m is thermal conductivity of matrix and ϕ_f is volume fraction of filler. De Loor (1956) also developed a mathematical model in equation (2);

$$K_c = \frac{K_m(1+\phi_f)}{1-2\phi_f} \tag{2}$$

where K_c is thermal conductivity of composite, K_m is thermal conductivity of matrix and ϕ_f is volume fraction of filler.

In an effort to improve on the earlier models, Nan et al. (2004) proposed equation (3);

$$K_c = \frac{K_m\left(3+\phi_f\left(\frac{K_f}{K_m}\right)\right)}{3-2\phi_f} \tag{3}$$

where K_c is thermal conductivity of composite, K_m is thermal conductivity of matrix and ϕ_f is volume fraction of filler.

The two basic models representing the upper and lower bound for thermal conductivity of composites are the rule of mixture also known as the parallel model and the series model (Ebadi-Dehaghani, 2012; Tavman, 1996). The former assumes perfect contact between particles and that each phase is assumed to contribute independently to the overall conductivity while the latter assumes no contact between particles and thus the contribution of particles is confined to the region of matrix embedding the particle. For the parallel model,

$$K_c = \phi_f K_f + (1-\phi_f)K_m \tag{4}$$

while for the series model,

$$\frac{1}{K_c} = \frac{\phi_f}{K_f} + \frac{1-\phi_f}{K_f} \tag{5}$$

where ϕ_f is the volume fraction of filler and K_m, K_f and K_c are thermal conductivities of matrix, filler and composite, respectively.

Researchers (like Ebadi-Dehaghani (2012), and Maxwell (1954)) obtained a simple relationship for the conductivity of randomly distributed and non-interacting homogeneous spheres in a homogeneous medium using potential theory:

$$K_c = K_m \frac{K_f + 2K_m + 2\phi_f\left(K_f - K_m\right)}{K_f + 2K_m - \phi_f\left(K_f - K_m\right)} \tag{6}$$

where, ϕ_f is the volume fraction of filler and K_m, K_f and K_c are thermal conductivities of matrix, filler and composite, respectively.

3. Materials

The polypropylene matrix is produced by Shiv Lila Polymers Ltd, Nigeria. It is in pellet form with a density and melt flow index of 0.90 Mg/m^3 and 58 g/10 min (230°C/2.16 kg), respectively. The particulate filler is iron ore tailings of irregular shape from the iron ore beneficiation plant in Itakpe, Kogi State, Nigeria. The chemical composition of the iron ore tailings is shown in Table 1.

Table 1. Chemical composition of Itakpe iron ore tailings

S/No.	Items	Composition (%)
1	Moisture	0.1487
2	Total organic carbon	0.6442
3	Total organic matter	0.7598
4	Fe_2O_3	0.2312
5	Copper	0.0061
6	Zinc	0.0018
7	Nickel	0.0013
8	Sodium	0.0051
9	Silicon oxide	61.4771
10	Calcium oxide	11.8924
11	Potassium	0.0012
12	Magnesium oxide	4.164
13	Chromium	0.0017
14	Cadmium	1.65E-06
15	Magnesium	0.0025
16	Aluminum oxide	20.663

Source: Abstracted from Adedayo and Onitiri (2012)

3.1 Methods

3.1.1 Fabrication of iron or tailings filled polypropylene composites

The iron ore tailings was dried at room temperature 30±2°C prior to fabrication of the composites (ASTM D618; ASTM E171 / E171M-11; ASTM E41-92), while the different particle sizes were generated using standard ASTM laboratory sieves (Adepoju and Olaleye, 2001; Olubambi and Potgieter, 2005). The uppermost of the ASTM sieve arrangement was loaded with iron ore tailings and vibrated for about 6 minutes.

After vibrating, the sieve arrangement was dismantled and the tailings deposited in each sieve were weighed. The results obtained from the particle size analysis carried out on the iron ore tailings has been reported in an earlier works by Adedayo and Onitiri (2012) and Onitiri and Adedayo (2015). The particle loading adopted in this work are 0 to 30 % at intervals of 5 % while the particle sizes are approximately; 53, 75, and 100 μm. The compo-indirect squeeze casting process was used for the fabrication of the iron ore tailings filled polypropylene composites. The process is discussed extensively by Onitiri and Adedayo (2015).

3.1.2 Tensile and thermal conductivity tests

The tensile test was carried out as specified in (ASTM D 638) with a test speed of 1.30 mm/min under standard laboratory atmosphere (ASTM E171; ASTM E41) on an Instrom 3369 testing machine. Prior to testing, the tensile test specimens were conditioned at room temperature for a minimum of 40 hours (ASTM E171; ASTM E41; ASTM D618; Onitiri and Adeniyi, 2003). The tensile test machine and procedure was discussed in a previous work (Onitiri and Adeniyi, 2003). The needle probe technique was used for thermal conductivity test on the iron ore tailings (ASTM D5334) and the composites (ASTM D5930) using the KD2 Pro meter kit produced by Decagon Devices Inc. The needle probe technique, also referred to as the line-source method, is a variant of the hot wire method (Sekhu and Singh, 2015; ISO 22007-1).

The TR 1 sensor was used for the thermal conductivity test. The needle probe was positioned at the center of the test specimen with both kept at constant initial temperature. A heat wave which propagates radially in the specimen is generated by producing a known amount of heat in the needle. The linear relationship between the temperature rise in the probe and the logarithm of time was used to obtain the thermal conductivity of the test specimen which is shown on a digital display unit. The tests were conducted on five specimens for each composite mix considered.

4. Results and Discussions

It could be seen in Figure 2 that minimum and maximum percentage retained weight of 0.22 % and 16.81 % occurred at aperture sizes 2000 µm and 300 µm, respectively. The approximate particle sizes (53 µm, 75 µm and 100 µm) considered in this work constitute over a quarter of the volume of iron ore tailings with a total percentage of 26.56 %.

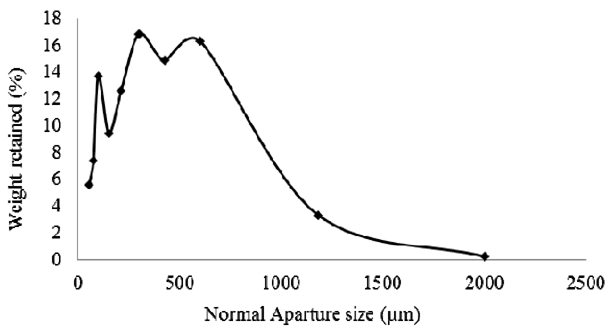
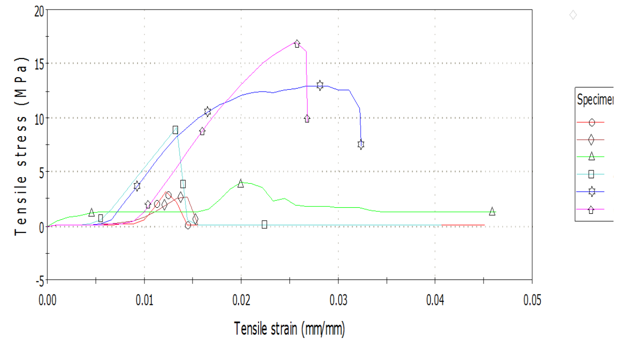


Figure 2. Weight retained versus normal aparture size

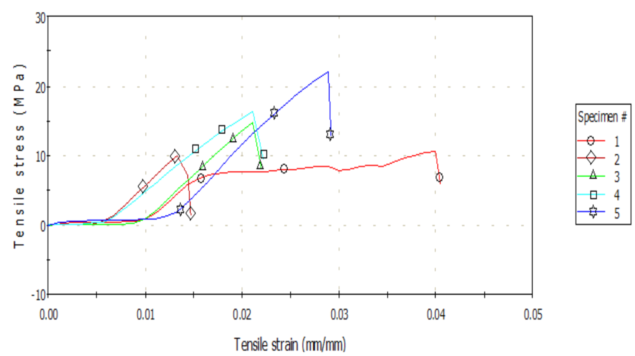
As shown in Figure 3, for 53 µm iron tailings particles filled polypropylene composites, they exhibited significant plastic deformation at low stress with decreasing particle loading with the highest strain of 0.05 at stress of 1.34 MPa for 15 vol. % particle loading. The maximum tensile stress increased with increasing particle loading with the highest value of 16.98 MPa for 30 % particle loading. This could be attributed to the increased contact surface area of the fillers which leads to enhanced matrix to filler bonding while the loading would reduce the formation of voids in the matrix which in this case would have been occupied by the fillers.

For 75 µm iron tailings particles filled polypropylene composites, Figure 4 shows that the tensile strength increases with increasing iron ore tailings filler with the highest value of 22 MPa at 25% particle filler inclusion and the lowest value of 10.50 MPa at 5 % inclusion. The highest tensile strain of 0.042 was recorded at 5 % addition of iron ore tailings.

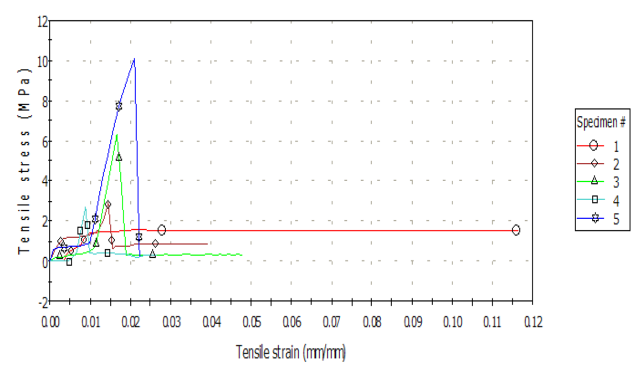
For 100 µm iron tailings particles filled polypropylene composites, Figure 5 shows that the addition of 25 vol. % iron ore tailings gave the highest tensile strength of 10.10 MPa and the least tensile strain of 0.023 while the addition of 5 vol. % of iron ore tailings produces composite with greatly improved strain at fracture of 0.116 and the least tensile strength of 1.60 MPa. This implies that the increased addition of 100 µm particle size iron ore tailings in polypropylene leads to improved tensile strength and decrease in the strain at fracture of the composite.



Figures 3. Stress-strain curves for PP filled with 53 µm iron tailings particles at loadings of (1) 5 %, (2) 10 %, (3) 15 %, (4) 20 % and (5) 25 %



Figures 4. Stress-strain curves for PP filled with 75 µm iron tailings particles at loadings of (1) 5 %, (2) 10 %, (3) 15 %, (4) 20 % and (5) 25 %



Figures 5. Stress-strain curves for PP filled with 100 µm iron tailings particles at loadings of (1) 5 %, (2) 10 %, (3) 15 %, (4) 20 % and (5) 25 %

Figure 6 shows the experimental thermal conductivity versus volume of 53, 75 and 100 µm iron ore tailings in polypropylene curves. It shows that thermal conductivity increases with increasing particle loading and reduces with increasing particle size. The former may be attributed to increased number of particle inclusions culminating to better particle to particle contact. The latter trend is caused by the increase in particle surface area which hinders better particle packing culminating to formation of inter-particle voids. These voids are either occupied by the matrix materials or air in the case of fabrication defects. Either of this development causes a reduction in the thermal conductivity of the composite. The highest thermal conductivity was experienced at the 30 vol. % inclusion with values of 0.376 W/m-K, 0.427 W/m-K and 0.394 W/m-K for 53 µm, 75 µm and 100 µm, respectively, compared to 0.175 W/m-K for polypropylene without inclusions.

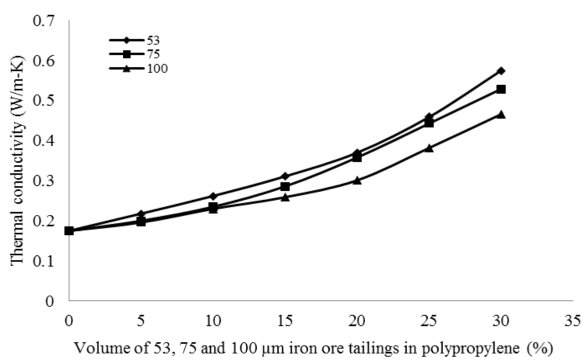


Figure 6. Thermal conductivity versus volume of 53, 75 and 100 µm iron ore tailings in polypropylene

It can be seen in Figure 7 that the experimental values are greater than the theoretical thermal conductivity values obtained from the mathematical models with the Bruggeman (1935) and De Loor (1956) model having the best prediction. This trend is observed for the other particle sizes considered. The lowest variation occurred at 0.01390 W/m-K and 0.0062 W/m-K for 5 % and 30 %, respectively.

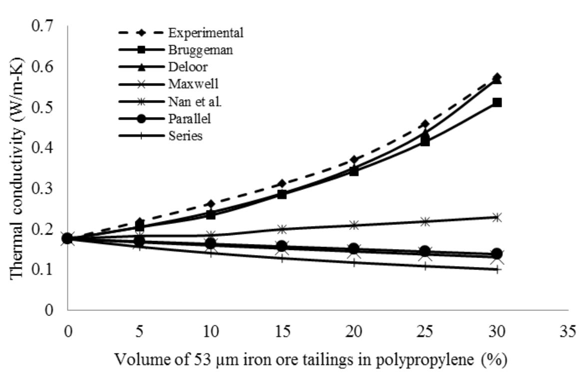


Figure 7. Thermal conductivity versus volume of 53 µm iron ore tailings in polypropylene

In the case of Figure 8, an improved predictability was observed for the Bruggeman (1935) and De Loor (1956) models while the other showed poor prediction with increasing particle loading. The Bruggeman (1935) and De Loor (1956) model showed lowest variation in predictability at 15 vol. % of filler; 0.0010 W/m-K and 0.0015 W/m-K, respectively. The De Loor (1956) model gave a perfect prediction at 27 % vol. inclusion. Figure 9 shows that their predictability reduces with increased volume content of particles with the lowest variation of 0.0081 W/m-K and 0.0082 W/m-K, respectively, recorded at 5 % vol. content.

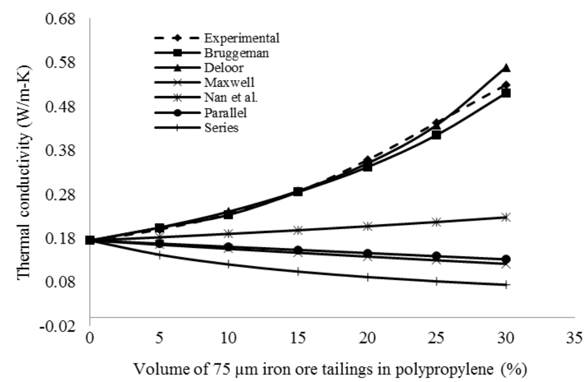


Figure 8. Thermal conductivity versus volume 75 µm iron ore tailings in polypropylene curves

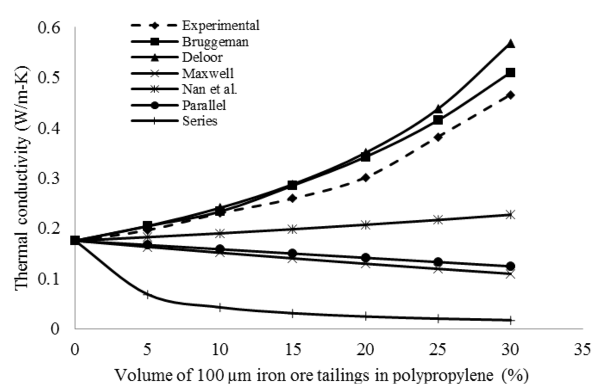


Figure 9. Thermal conductivity versus volume of 100 µm iron ore tailings in polypropylene

5. Conclusion

It was discovered that the maximum possible iron ore tailings inclusion in polypropylene is 30 vol. % for 53 µm particle size while for 75 µm and 100 µm is 25 vol. %. The addition of iron ore tailings in excess of the vol. % indicated led to extreme structural instability of the composite. The composite with particle loading of 25 vol. % gave the highest tensile strength for particle sizes 75 µm and 100 µm. Besides, it was found that thermal conductivity increases with increasing particle loading and reduces with increasing particle size. The maximum value of 0.575 W/m-K was recorded at 30 vol. % of 53 µm.

The model proposed by Bruggeman (1935) and De Loor (1956) gave the best reasonable predictions of the thermal conductivity of the composites for all the particle sizes considered. The best prediction for the two models occurred at 75 µm particle size and it improves with reducing percentage volume of filler. It is interesting to note that the predictability of the Maxwell, Nan et al. (2004), parallel and series models exhibited poor predictability with increasing volume inclusion and for all the particle sizes, with the latter exhibiting increased poor prediction with increasing particle size.

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Investigation of Cocoa Pod Husk Mechanical Behaviour and the Impact upon Specific Cutting Energy

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Abstract: *Theobroma Cacao, or Cocoa, is well known for its use in the production of chocolates. Traditionally, the cocoa pod husk has been considered a waste by-product and has been poorly disposed of. However, in recent times, there has been a growing interest in the use of the husk, as research has unveiled many new potential applications. Most of these generally involve comminution of the husk, i.e., its shredding or cutting. Despite this, the literature has been silent regarding the cutting of the husk and the associated energy requirement. This work investigates the energy requirement for the cutting of cocoa pod husk. Firstly, it uses a Universal Testing Machine to determine the force required and energy absorbed in the tensile testing, compression testing and cutting of the husk. It then uses a typical shredding machine to determine the specific cutting energy for producing chips of quarter inch length. Lastly, the work examines the impact of cutting speed on specific energy consumption. The results indicated that specific cutting energy increased with cutting speed, with an observed maximum of 1.63 J/g. It was concluded that cutting at slower speeds is preferable, as it leads to lower energy consumption. Further, it was also found that more energy is required in the cutting of the husk, than in its separation via pure tension. Samples of similar dimensions absorbed a mean of 0.527 J in the cutting process, while a mean of 0.185 J was absorbed in separation via pure tension. Accordingly, an alternative size reduction process to cutting may be more effective in decreasing the associated energy consumption of comminution.*

Keywords: *Cocoa, pod husk, specific cutting energy, tensile testing, cutting force, mechanical behaviour*

1. Introduction

Cocoa, or Theobroma Cacao, is a small tree that is native to the tropical region. The seeds of the cocoa fruit or cocoa pod, are a well sought-after commodity. Cocoa beans, as they are more commonly referred to, are the base material for the production of chocolate and its related products. The beans are also the source of cocoa butter, which has extensive uses not only in chocolate production, but in the cosmetics, pharmaceuticals and nutraceutical industries (Fairtrade Foundation, 2019). Accordingly, cocoa represents a significant contributor to the economies of cocoa growing countries, such as, Cote D'Ivoire, Ghana and Indonesia, and they have made significant investments in the development of cocoa agriculture (Fairtrade Foundation, 2019). In keeping with this, much effort has been directed towards the development of large-scale cocoa bean processing equipment and facilities, and this is a well-developed industry (Fairtrade Foundation, 2019).

Cocoa bean harvesting necessitates the removal of the cocoa beans from the pod, leaving behind the pod shell or husk. The husk is approximately 76% of the cocoa pod's mass and therefore represents a major by-product of the cocoa bean harvesting process (Vriesmann and de Oliveira Petkowicz, 2017; Chan and Choo, 2013). Traditionally, this has been considered to be a waste product with minimal value (Chan and Choo, 2013). However, its uses have increasingly evolved over time, as more knowledge of its constitution becomes available. Some more rudimentary uses of the husk include its use as animal and fish feed (Adzimah and Asiam, 2010) (Ridzwan et al., 1993). These often require little to no processing of the husk.

More complex uses of the husk have been reported in recent times. Adzimah and Asiam (2010) reported on the use of the pod husk in the development of potash fertilizer, local soaps and in the production of particle board. This is a consequence of the husk's high potassium content. Vriesmann and de Oliveira Petkowicz (2017) have reported on the extraction of pectins from cocoa pod husk, which are highly acetylated and capable of gelling in acidic media. Chan and Choo (2013) and Priyangini, Walde, and Chidambaram (2018) have also reported on similar work. The implications of these works are significant for the food industry. El-Shekeil, Sapuan, and Algrafi (2014) have used cocoa pod husk in the development of reinforced thermoplastic composite materials. Their investigations indicated that the flexural strength of the composite increased with increasing cocoa pod husk fibre content. de Luna et al. (2017) have investigated the use of activated carbon derived from cocoa pod husks, as an adsorbent for the removal of sodium diclofenac from waste water and other aqueous solutions. Moreover, Khanahmadi et al. (2015) in their work were able to develop stable cross-linked enzyme aggregate lipase from cocoa pod husk. The husk based cross-linked enzyme aggregate was found to demonstrate better enzymatic activity than the free enzyme reference comparison. Their work found the husks to be quite effective. In almost all cases, the cocoa pod husk underwent a size reduction process of some sort, before its use in the specific application.

A more novel application of the husk that is perhaps of greater significance, is its use in energy applications. Increasingly, various researchers have been investigating and developing alternative methods for the utilization of cocoa pod husk for power generation. Khanahmadi et al. (2016) have successfully used cocoa pod husk derived enzymes as catalyst in the production of Jatropha biodiesel. Similarly, Ofori-Boateng and Lee (2013) have used cocoa pod husk derived potash, as a catalyst in the successful transesterification of soybean oil to biodiesel. In a related bit of work, Rachmat, Mawarani, and Risanti (2017) have also used cocoa pod husk as activated carbon and a catalyst in the production of biodiesel from waste oil sources. Further, Adjin-Tetteh et al. (2018) have investigated the development of bio-oils via pyrolysis of cocoa pod husks and have found that 58% of the processed husk can be recovered as useful bio-oils. Syamsiro, Saptoadi, and Tambunan (2011) investigated the use of cocoa pod husk-based bio-pellets as a solid fuel source and concluded that it has similar combustion characteristics to other biomass sources. Syamsiro, Saptoadi, Tambunan, and Pambudi (2012) investigated the use of carbonized, crushed cocoa pod husk as a renewable fuel. It was found to have a high heating value of 17 MJ/kg, which is approximately one-third the value of petro-diesel. More broadly, they investigated the suitability of cocoa pod husk as a fuel source, for use in the Indonesian context. Yet, Dahunsi, Adesulu-Dahunsi and Izebere (2019), and Dahunsi et al. (2019) have both investigated the use of pre-treated cocoa pod husk for biogas generation. Their work indicated that the pre-treatment methods employed, significantly aided in increasing the biogas output of cocoa pod husk anaerobic digestion.

In almost all of the aforementioned cases, a primary step in the use of the cocoa pod husk is its comminution, i.e., disintegration into smaller pieces. This generally increases its surface area and facilitates use in the subsequent steps. Comminution forms part of the wider pre-treatment process of the biomass material and requires the input of energy. However, the pre-treatment processes associated with biomass preparation for energy applications are often energy-intensive; they have been known to consume up to 20% of the energy yielded from the biogas produced (IEA Bioenergy, 2013). This negatively affects the energetic feasibility of the biomass's use as an energy source. More specifically, comminution has been found to be one of the highest energy consuming components of the pre-treatment process, accounting for as much as 5% of the biomass's energy content (Miao et al., 2019; SciTech, 2019).

Accordingly, minimising the energy consumption of the comminution process is a critical concern in the use of biomass for energy purposes. Consequently, researchers have investigated the impact of various machine parameters on the cutting energy of different crops. Mathanker, Grift, and Hansen (2015) investigated the impact of blade oblique angle and cutting speed upon the cutting energy of energy cane stems. They reported that specific cutting energy increases with cutting speed. Allameh and Aliza (2016) investigated the impact of varying blade parameters upon the specific cutting energy of rice stem cultivars. Among other things, it was found that cutting speed directly influenced specific cutting energy. Igathinathane, Womac, and Sokhansanj (2010) have investigated the impact of corn stalk orientation upon its specific cutting energy. They found that a parallel orientation is preferred to a perpendicular one, as it significantly decreases the cutting energy required. Johnson, Clementson et al. (2012) investigated the impact of oblique angle and cutting speed upon the specific cutting energy requirement of miscanthus giganteus stems. They also found that specific cutting energy was directly proportional to cutting speed and cutting energy was proportional to stem diameter. Kakahy et al. (2014) have looked at the impact of blade cutting angle and cutting speed upon the specific cutting energy of sweet potato vines, and were able to identify the optimal conditions for low energy consumption.

However, despite the increase in the investigation of cocoa pod husk for energy applications, the literature has been mostly silent on work regarding the energy consumption of its comminution process. In keeping with this, the authors of this work sought to determine the energy consumption required in the development of cocoa pod husk chips. Moreover, to examine and understand the impact of variations in the cutting parameters upon the energy required in the production of the husk chips. In so doing, the authors seek to identify the optimal conditions necessary for the size reduction process of cocoa pod husk and to be able to make recommendations regarding the minimisation of the associated energy consumption.

2. Materials and Methods

2.1 Shredding Machine

For the purposes of this test, a shredding machine was developed to produce 0.25-inch (6.35 mm) length cocoa pod husk chips. The machine is similar in design to that of a typical shredder used for the size reduction of other biomass material. It is composed of five major components; the body, motor, cutting chamber, cutting shaft and the catchment bin as seen in Figure 1.

The machine functions by placing the cocoa pod husk in a hopper at the top. The husk then falls into the cutting chamber where it meets the cutting shaft, which carries a series of blades that passes through a fixed cutting plane with a 3/4 inch spacing. The machine utilizes a staged cutting process for gradual reduction of the husks, together with a discharge screen for production of standard size cuts. After the first cut, the chopped husk falls to a second cutting plane with a half-inch space, producing smaller cuts. Subsequently, this passes on to the last cutting plane producing ¼ inch chips. The chips finally exit at the bottom of the machine, and freely fall into a storage bin located below the cutting chamber. The cutting shaft is turned by a 1.5 hp motor, which is securely mounted on the frame of the machine. The motor was fitted with a variable frequency drive, which allowed its speed to be varied and set to specific values.

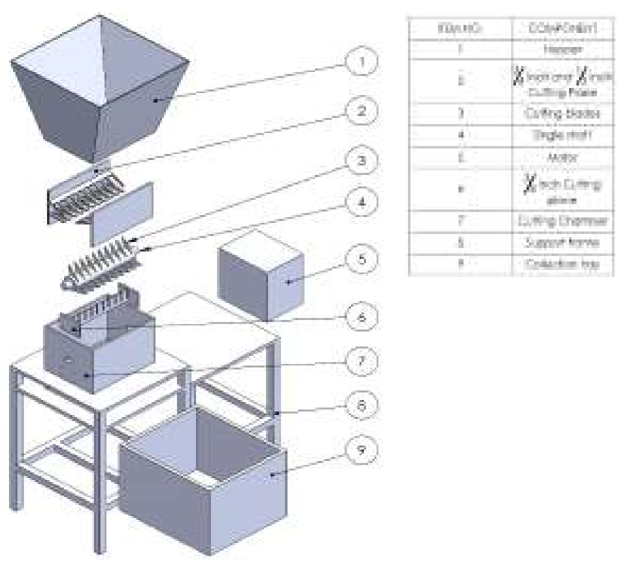

Figure 1. Exploded view of shredding machine used in the testing process

2.2 Testing Methodology

2.2.1 Tensile and Compressive Tests

The test procedure comprised of three distinct phases. The first phase sought to determine the response of the cocoa pod husk to pure tension and pure compression forces. The information obtained from these tests would give insight into the energy required for separation of the husks via pure tension and/or pure compression. For the purposes of these tests, a Tinius Olsen H25KS Universal Testing Machine (UTM) was employed. For the pure tension force tests, cocoa pod husk samples were obtained by splitting cocoa pods and removing the contents (the cocoa beans). The husks were then manually cut into rectangular samples of dimensions 75 mm by 27 mm, with an average thickness of 11.5 mm. The sample was placed between the jaws of the UTM, in the manner that is specified for standard tensile tests (see Figure 2). The sample was then subject to a strain rate of 10 mm/minute and underwent extension until failure. The data was recorded by the UTM, which subsequently presented a graphical illustration of the sample's behavior under load. This was then repeated for five samples and the mean values of key parameters are presented in Table 1.

In a similar manner, husk samples were prepared for compression testing. The average dimensions of the samples used were 51 mm in length, 15 mm in width and a thickness of 8.5 mm. The samples were placed between the jaws of the UTM, in a manner that is specified for standard compression tests. The samples were then compressed to approximately 1.5-2.0 mm thickness, at which point the machine was stopped. The data was recorded by the UTM and presented graphically. As in the tensile tests, these tests were repeated for five samples and the mean values of the parameters recorded are presented in Table 1.

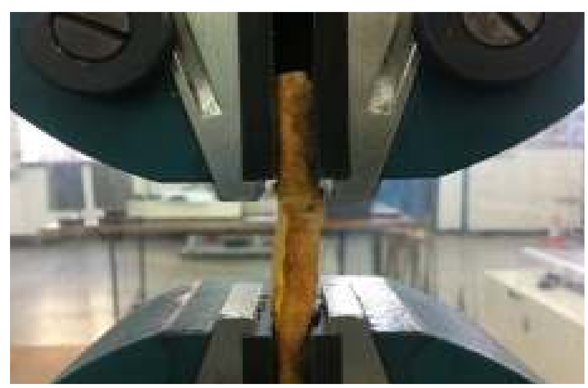

Figure 2. Orientation of cocoa pod husk samples in UTM tensile tests

Table 1. Mean values obtained from pure tension and cutting tests

Test type	Mean value of force (N)	Maximum force observed (N)	Minimum force observed (N)	Mean extension (mm)	Mean stress (MPa)	Mean energy absorbed (J)
Pure tension	82.4	110	51.7	3.31	0.335	0.185
Pure compression	11830	13700	10500	-10.14	15.2	14.38
Cutting	124	152.5	87.5	-10.74	0.474	0.527

2.2.2 Cutting Force Tests

The second phase of the tests, sought to determine the response of the cocoa pod husk to a cutting force. This was conducted using the UTM used in phase 1 of the testing. However, in this instance the UTM was retrofitted to include a cutting blade, as shown in Figure 3. This arrangement allows for the determination of the energy required in separating the husk using pure shear force. As in the first phase, rectangular cocoa pod husk samples were manually produced. The samples were of dimensions 26 mm by 26 mm, with an average thickness of 11 mm. The test speed of the UTM was set to 10 mm/minute and the test was allowed to proceed until the blade progressed through at least 8mm of the sample's thickness. The data was once more recorded by the UTM and presented via a graphical interface. These tests were also repeated for five samples and the means of the same parameters identified in the phase-1 tests, are presented in Table 1.

Figure 3. Orientation of the cocoa pod husk samples in the UTM cutting force tests

2.2.3 Shredding Machine Tests

For the third phase of testing, the tests sought to determine the energy consumed in shredding the husk using a shredding machine. More specifically, this phase investigated the impact of a change in cutting speed of the machine, upon the energy consumed in the shredding process. As in the first phase, cocoa pod husk samples were obtained by splitting cocoa pods and removing the contents. The mass of the husks was determined by use of an electronic scale. The motor speed was set to 600 rpm, the machine was started and it was allowed to run until the shaft arrived at the set speed. Once at the prescribed speed, the machine's power consumption was measured by use of a wattmeter. The husks were then thrown into the hopper and allowed to be shredded by the machine. During the process, the wattmeter was used to measure the power consumption of the machine. The time taken for complete shredding was recorded via a stopwatch. Once the mass was completely shredded by the machine, the machine was turned off. The mass of the chips collected in the bin was weighed and a sample of twenty (20) chips were measured with a Vernier caliper, to determine their lengths. The entire process was repeated three times for the initial speed of 600 rpm, with the same data being recorded on each repetition. The motor speed was then set to 720 rpm and the process was repeated, recording the same data as before. The entire testing procedure was further repeated for motor speeds of 840 rpm, 960 rpm, 1080 rpm and 1200 rpm and the means of the recorded parameters are presented in Table 2.

3. Results and Discussion

3.1 Tensile, Compressive and Shear Force Cutting Results

Figure 4 shows an example of the force-displacement curve obtained from the UTM for the cocoa pod husk samples undergoing pure tension. As can be seen in the figure, the tensile force in the sample sharply increases as it is extended. This increases to a peak value, which is associated with the initiation of failure of the sample. Subsequently, the force in the sample decreases to zero as the sample is split into two separate pieces.

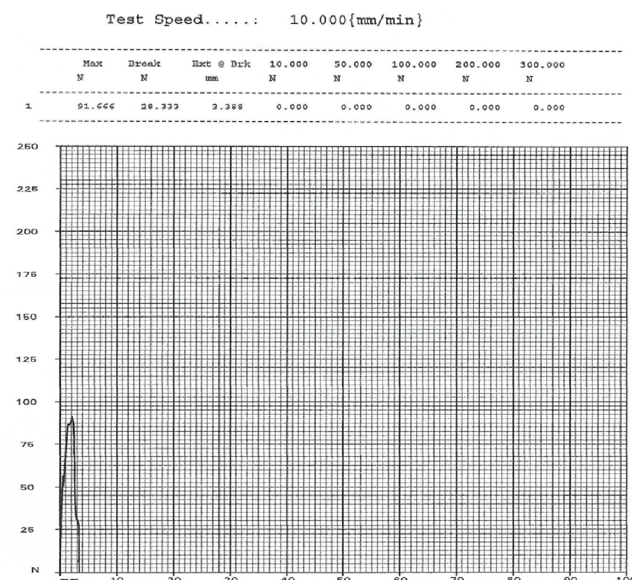

Figure 4. Force-displacement curve for samples in pure tension tests

The increase in force as the sample is initially extended, is expected. This is common behaviour for most materials undergoing tensile tests, and is associated with the increasing stress in the sample until failure. The rapid increase however, is indicative of the lack of elasticity in the sample. As mentioned earlier, the peak force is associated with the initiation of failure in the sample. The mean value of the peak force obtained from the five tests, was found to be 82.4 N as seen in Table 1. This force showed a range of approximately +/- 30 N, with the highest value recorded as 110N. The mean peak value corresponds to a stress of approximately 0.335 MPa. Accordingly, the area under the graph of Figure 4 is associated with the energy required for the separation of the sample, via pure tension. The mean value of this energy was found to be 0.185 J. As a reference, these values are low compared to those obtained for corn stalks samples, as reported by Igathinathane et al. 2010.

An example of the force-displacement curve obtained for the compression tests is shown in Figure 5. In the figure, there are three distinct regions visible in the force-displacement profile. The first is a region of a slow increase in the compressive force with the increase in negative extension. This occurs for the first 2 – 3 mm of compression. After this region, the compressive force begins to increase more rapidly with increasing compression. This occurs for approximately the next 4 – 5 mm of negative extension. Beyond this, there is a sharp increase in the compressive force as the sample continues to be compressed. This occurs until the machine is eventually stopped, at which point the peak value of forces is recorded. It is interesting to note that at the end of this process, the samples removed from the machine though crushed, are not broken into more than one piece.

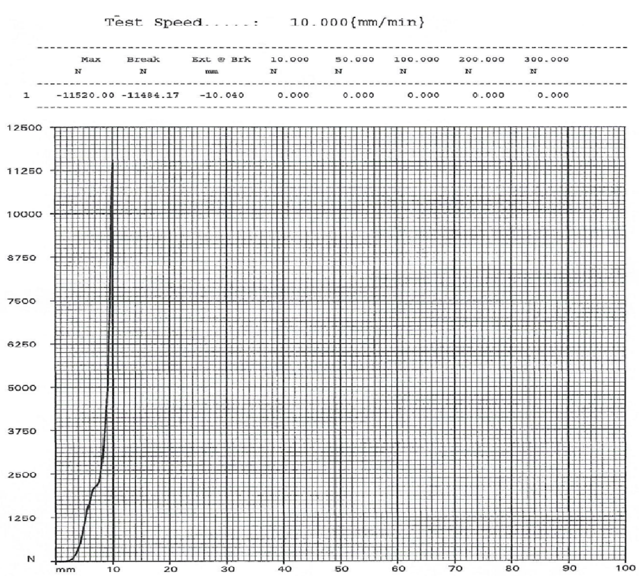

Figure 5. Force-displacement curve for samples undergoing pure compression

The profile produced from the compression tests is rather intriguing. The first region of the profile indicates that the sample is able to withstand lower values of compressive forces with minimal to zero negative extension. This indicates that the husk has the potential to buffer the impact of smaller forces that are applied in this manner. The second region on the graph shows an approximately linear relationship between compressive force and negative extension. This region was found to generally range for approximately 1500 – 1800 N. Beyond this, the profile transitions to the third region. Though the final samples were not observed to be broken upon completion of the tests, it is believed that at this point there is a failure in the mechanical integrity of the sample. The further rapid increase in the compressive force is believed to be attributed to the increasing force between the jaws of the machine. However, it is not believed that the sample provides any further resistance to compression at this point. In keeping with this, the mean value of the energy absorbed is 14.38 J.

Figure 6 shows an example of the force-displacement curve obtained for the samples when separated by cutting. It can be seen that for the first portion of the profile, the extension increases almost linearly with increasing cutting force. This rises to a peak value, which is believed to be the point at which failure initiates. Beyond this point, the value of the cutting force varies in a nondeterministic manner until the point of failure or machine stops. It should be noted that the machine records this extension as negative, similar to the compression tests.

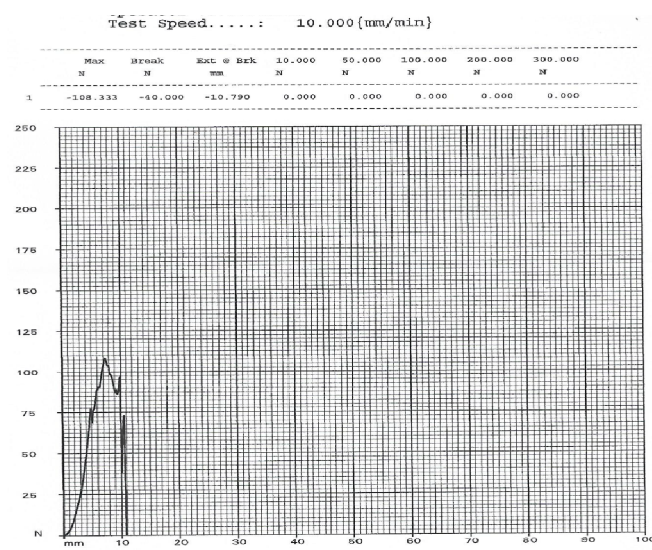

Figure 6. Force-displacement curve for samples undergoing cutting

As reported in Table 1, the mean value of the peak force associated with cutting is approximately 124 N and the associated stress is approximately 0.474 MPa. This force is also found to have an approximate range of +/- 30 N, with the highest recorded value being 152.5 N. In keeping with this, the mean value of the energy absorbed during the separation process, or the cutting energy is 0.527 J.

A comparative examination of Figures 4, 5 and 6, yields some critical insight into the nature of the husk and potentially into its cutting dynamics. Firstly, it is evident from Figures 4 and 5 that the forces and energy associated with compression are significantly higher than that associated with tension. More importantly, it can be seen that for the same value of force, the extension associated with compression is much lower than that associated with tension. Thus, the values of tensile force that led to failure, when applied in compression result in minimal impact upon the husk.

Further in considering the pure tension and cutting profiles, it is evident that the force-displacement profile produced by cutting, is unlike that of pure tension in two key ways. Firstly, unlike the pure tension profile that has only one peak value of force, which is associated with the maximum force at the initiation of failure, the cutting profile illustrates more than one peak point. These peaks generally occur after the maximum value that is associated with the initiation of failure and are lower than this value. This variation in the force and the presence of additional peaks as a feature of the cutting process, is a consequence of the cocoa pod husk sub-structure. Though not exactly similar to the profiles obtained here, the cutting profiles for corn husk presented by Igathinathane et al. 2010 also illustrated force variations of this nature during the cutting process. The authors also attributed this to a similar cause.

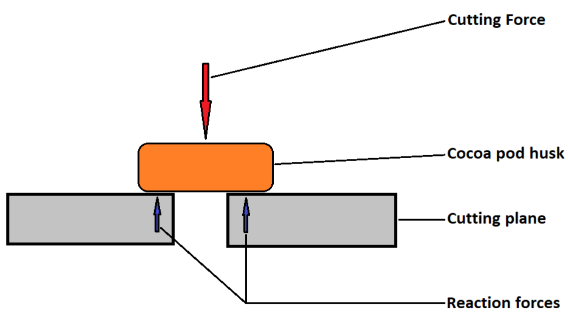

Figure 7. Schematic of cocoa pod husk interacting with cutting force

The second feature identified from a comparison of these figures is perhaps of greater interest. The extension and consequently strain associated with the cutting profile, is in general two to three times more than that of the pure tension profile. It is evident from the pure tension profile, that the samples do not demonstrate high levels of elasticity. Thus, the increased extension cannot be attributed to the samples' tensile behaviour. However, as can be seen in Figure 7, the cutting of the sample leads to bending. Given that bending results in both compression and tension, with compression occurring on the upper face in contact with the blade, it is likely that this increased extension is due to compression. More specifically, the increased extension can primarily be attributed to the negative strain associated with the compression that occurs in the cutting process. Accordingly, this results in a greater quantity of energy being absorbed during cutting than in separation via pure tension.

It is suggested that a more significant implication of the foregoing results, lies in the wider consideration of the cocoa pod husk comminution process. A typical shredder was used in the size reduction process of these tests, as this is often employed in biomass size reduction. However, given that the compressive strength of the cocoa pod husk is significantly greater than its tensile strength, the resulting energy consumption during cutting is higher. More specifically, the energy consumption of failure by cutting is approximately 2.85 times more than that associated with failure by pure tension. Consequently, though shredders or cutters are often employed for size reduction of biomass material, the preceding results suggest that for cocoa pod husk a different comminution process may be more effective in minimising the energy consumption. More specifically, a comminution process that employs more tensile forces than compressive forces, such as abrasive grinding, may be more suitable than shredding.

3.2 Impact of machine cutting speed

Table 2 shows the results obtained for the machine shredding of the cocoa pod husk, at the six machine speeds. The machine output was determined using the recorded values for the mass of husk put into the machine, the mass of chips obtained and the time taken for this to occur as given by Equation (1). In general, the output stayed within a particular range for the variations in speed. This is primarily a function of the machine and the manner in which it is fed. Further, the total power consumption of the machine increased with increasing cutting speed. This is somewhat expected, as the machine would require greater energy to facilitate the increased speed of rotation of the cutting shaft. However, the power used in shredding, which was the difference between the operational and no load power values, was found to fluctuate.

$$\text{Machine output} = \sum_{i=1}^{n}\left[\frac{Input\ mass\ (g) - Output\ mass\ of\ chips\ (g)}{time\ taken\ (s)}\right]^{i} \Big/ n \quad (1)$$

$$\text{Specific cutting energy} = \sum_{i=1}^{n}\left[{Operational\ power\ consumption} \big/ {Machine\ output}\right]^{i} \Big/ n \quad (2)$$

where, n is the number of repetitions.

More importantly, however, Figure 8 shows the relationship between cutting speed and the specific cutting energy in joules per gram. On average, the specific cutting energy ranged from 1.29 to 1.63 J/g. Moreover, it can be seen from the figure that the specific cutting energy generally increases with increasing speed. The relationship is not necessarily entirely linear in nature, as evidenced by a correlation coefficient of 0.52 and it implies that there are other influential factors. This is in keeping with the results obtained by Mathanker et al. 2015, who reported similar correlation coefficients. Nonetheless, the results indicate that the influence of speed on the specific cutting energy is a significant one.

This is likely attributed to the cutting dynamics observed previously and illustrated by Figure 6.

Table 2. Data obtained from machine tests

Cutting speed (rpm)	Machine output (g/s)	No-load power consumption (W)	Operational power consumption (W)	Power used in shredding (W)
600	5.84	67.33	74.84	7.51
720	6.62	75.33	83.96	8.63
840	5.78	82.33	90.07	7.74
960	6.90	90.67	101.82	11.15
1080	6.62	104	112.88	8.88
1200	6.23	119	128.41	9.41

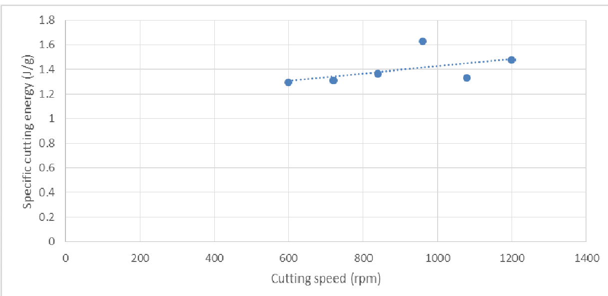

Figure 8. Cutting speed (rpm) vs. specific cutting energy (J/g)

Given that the shredding machine used is actuated by a motor of fixed power, an increase in cutting speed will result in a concomitant decrease in the torque and consequently the cutting force available at the blades. With the requisite value of force not always available at each instance of an interaction between the blades and a piece of husk, the husk is either partially cut or simply absorbs the energy of the blade and is deflected. In either case, this results in less cuts per revolution. Accordingly, more rotations will be required to produce the same output and consequently more energy is consumed per unit output. A more in-depth analysis of the cutting dynamics is required to fully verify this behaviour. Notwithstanding, the results indicate that cutting at lower speeds is preferable, as it consumes less energy to generate the same output. This however is predicated upon the required values of cutting force being available at the lower machine speeds.

As mentioned previously, a sample of husk chips was obtained for each cutting speed of the machine and measured to determine the length of its longest side. The recorded lengths of the sample sets were assessed to determine the statistical significance of the differences between individual sets. This assessment involved conducting pairwise comparisons of each set against the other, using a 95% confidence interval. The assessments were done using the Microsoft Excel, Analysis ToolPak solver add-in. The result of each assessment is a t-Stat value; here a t-Stat value of magnitude greater than 2.5, indicating a significance in the difference between the mean values compared. In keeping with this, Figure 9 shows the change of mean chip length with change in cutting speed, while Table 3 shows the results of the statistical assessments. It can be seen from Figure 9 that the mean length of the chips measured, varies from 6.86 – 7.87 mm. The results of the statistical assessment indicate that the differences in the means observed for each speed are of no statistical significance. Thus, this implies that the impact of cutting speed upon mean chip size is minimal. As a consequence, there appears to be no preferable speed with respect to the quality of products obtained from the machine.

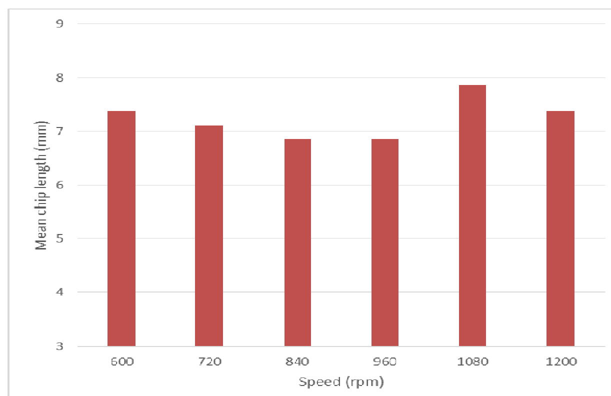

Figure 9. Cutting speed vs. mean chip length (mm)

Table 3. Results of t-Test statistical pairwise comparison assessment

t-Stat	**600 rpm**	**720 rpm**	**840 rpm**	**960 rpm**	**1080 rpm**	**1200 rpm**
600 rpm	–	0.65	1.34	1.13	-0.75	0.11
720 rpm	0.65	–	0.47	0.32	-0.98	-0.53
840 rpm	1.34	0.47	–	-0.16	-1.5	-0.91
960 rpm	1.13	0.32	-0.16	–	-1.64	-0.95
1080 rpm	-0.75	-0.98	-1.5	-1.64	–	0.63

4. Conclusion

This work sought to determine the energy associated in the size reduction via cutting of cocoa pod husks. Cocoa pod husk samples were tested in a universal testing machine to determine the energy required for separation via the use of pure tension, pure compression and via shear cutting. The mean peak force required for failure via pure tension was observed to be 110 N and the energy required was 0.185 J. Conversely, the husk samples showed great resistance to compressive loads. Peak forces of up to 13.7 kN were observed during compression tests, with the samples still largely intact after testing. However, as in the case of the tension tests, the cutting tests led to clear separation of the samples but the values of peak force obtained for failure via cutting were observed to be higher. The associated mean peak force was recorded as 152.5 N and the cutting energy required was 0.527 J. Further, when specific cutting energy was examined via a shredding machine, it was found that it generally increased with cutting speed, with an observed maximum of 1.63 J/g. On the other hand, the impact of cutting speed upon the size of the chips produced was found to be minimal. It is believed that the decrease in cutting force with increasing speed, leads to the requirement for greater energy consumption in the cutting process. Ultimately, due to the behaviour of the husk samples during cutting, it can be recommended that cutting of husk be done at lower cutting speeds. Providing the values of cutting force are attainable by the machine at these speeds, lower speeds are preferable as they result in lower energy consumption levels. Moreover, the energy consumption associated with failure via pure tension was found to be 2.85 times less than that by cutting. Thus, though cutting or shredding is often used, it is believed that comminution via an alternative process such as abrasive grinding may be more effective in decreasing the energy consumption associated with the process.

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A Compact Urban Aquaponic Irrigation System for the Caribbean Region

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Abstract: *Alternative techniques with cost-effective integration of various production units have been developed as the possible solution of feeding the ever-increasing population in a sustainable way. Aquaponic irrigation system is one such technique that is being utilised to face the many challenges of conventional cultivation. Aquaponics is the integration of circulatory aquaculture system and hydroponics, with the utilisation of beneficial bacteria for safe fish and plant production. A prototype aquaponic system, designed to suit the climatic conditions of Trinidad and Tobago was constructed and tested alongside a conventional soil-based farming system. The aquaponic system consisted of a 946 L fish tank where 20 tilapia (Oreochromis niloticus) fishes were reared. The tilapia fishes were fed with a commercial floating fish feed and the fish waste water produced was filtered and the effluent was then used to irrigate the hydroponic beds which comprised of 130 plants. Tests showed that the performance of the aquaponic system was better than that of the conventional farming system in terms of shoot diameter, plant height and the number of leaves present. This was attributed to the developed state of the bacteria colony in the aquaponic system which allowed for the conversion of the ammonia quickly and resulted in a high average nitrate level needed for plant growth. The survival rate of the fishes was 90% and the tilapia fishes experienced an average weight gain of 167.80 % during the testing period of two months. The performance of this aquaponic system is encouraging and could be used in an urban setting.*

Keywords: *Aquaponics, irrigation, aquaculture, hydroponics, environment, Trinidad and Tobago*

1. Introduction

The predicament facing the global community ponders on the question of how future generations in urban locations will produce more food on a sustainable level. The traditional agricultural approach has shown itself to be unsustainable as it has substantial environmental impact on the natural resources which poses serious issues such as the reclamation of virgin land for agricultural purposes, chemical usage and nutrient leaching (Rohila et al., 2017). According to Shik et al. (2018), agriculture only contributes 0.5% to the gross domestic product (GDP) of Trinidad and Tobago's economy and with the present demand plaguing the sector for organic and pesticide-free produce (Narine et al. 2015), health conscious citizens are now contemplating of growing their own food using modern cultivation methods.

According to Fields (2004), over the last 25 years of nitrogen use in most of the leading chemical fertilisers has surpassed the nitrogen content in oceans by 20 times and this have resulted in severe eutrophication to the water bodies. It is therefore of paramount importance that this nitrogen loop between crops and animals is closed or strongly minimised as a solution to improve the water quality and nutrient efficiency while simultaneously reducing wastes. Research by Wahyuningsih et al. (2015) on nitrogen efficiency shows that aquaponic model is becoming the alternative way of the treating nitrogen and addressing the crisis that traditional agricultural approaches pose.

Ebeling et al. (2006) proved the preceding narrative as they showed that 80% of the nitrogen waste from fish in the system is further broken down for intake by plants, making the aquaponic model a very sustainable practice that should be further analysed as it also results in maximising land use along with water quality and efficient nutrient use. The article by Ebeling et al. (2006) shares the view that the aquaponic model can have particular attractions in urban locations especially where the water use and soil medium may be limited, and where there is growing demand for both fish and organic vegetables. With growing interest and the potential relevance of aquaponics as a sustainable method of producing organic pesticide-free foods, there needs to be further discussion regarding the potential of the aquaponic model for users in urban environments to meet their needs. The main dilemma that persons from urban settings face is that the majority of persons do not have a lot of time to tend to their traditional backyard gardens due to their hectic schedules and many do not have large spaces dedicated for growing the volumes of organic produce needed. The aim of this paper is to design an urban aquaponic system that addresses these pertinent issues and provides adequate conditions for crop growth and fish survival. It will allow the customer to use the system for both home-use and/or small entrepreneurial business prospects. The system will be labour extensive and would be as compact as possible to meet the client's needs but at the same time it would consider durability and cost effectiveness. Specifically, this paper will test and analyse the ammonia content and water quality of an aquaponic system that incorporates both mechanical and bio-filtration methods; test and analyse the system using key variables including plant and fish growth and compare the growth of plants in the aquaponic system to those grown conventionally in soil.

2. Basic Concepts Involving Aquaponic Systems

Hydroponics is the method of cultivating plants using only water, nutrients and a suitable soil-less growing medium. Only the plant roots are exposed to the mineral solution. The nutrient solution is formulated from inorganic or organic hydroponic solutions, additives and mixed solution (Turner, 2017). Many systems of hydroponics exist including the media-based technique, nutrient film technique (NFT), raft technique, flood and drain technique and deep-water culture technique (Nelson 2008). In the media-based technique, plants are cultivated in beds, pots or bags and several media options include organic media options such as straw, bark, peat, sawdust and seaweed, while mineral options include sand, perlite, rock wool, expanded clay balls and gravel (Fox et al., 2010). There are also synthetic media options such as expanded clay ball, polyurethane and polystyrene (Resh, 2016). The NFT technique is widely used in commercial hydroponic systems and involves having a thin layer of nutrient rich water flowing from the reservoir tank to tubes or closed gutters.

Aquaculture is used to produce a variety of species such as fresh and saltwater fishes, molluscs and crustaceans (NOAA, 2012) in a full or semi-controlled system. Fish farming is the primary form of aquaculture today because the ocean's resources are being stressed out while seafood demand has reached unprecedented levels (Bostock et al., 2010). The aquaculture model is faced with several issues which range from the limited genetic variation, the propagation of diseases and the system's ability to manage waste produced (Davidson and Summerfelt, 2005). Often what is done to negate these issues is to have a large water volume exchange which helps maintain the water quality at non-toxic levels but this is found to be economically unfeasible for lengthy periods (Bostock et al., 2010). The solution to this is re-circulated aquaculture systems (RAS). In RAS, the waste water produced in the fish tanks is recycled and fed back to the fish tank source after passing through mechanical and bio-filters (Somerville et al., 2014). In this system, however, the solid waste removal deficiency occurs in the settling tank as well as in the bio-filters where there is excessive organic sludge build-up.

Urban aquaponic farming is the practice of combining fish and soilless plant production in an urbanised town or city where there is limited space for farming (Smiley, 2012). The nutrient rich waste produced by the aquaculture component is circulated through the hydroponic component where the nutrients are absorbed by the plants after which the water is recycled to the fish tank. Urban aquaponic farming helps in maximising land space, water and nutrient use efficiency and addresses the quality aspect of the food produced.

3. Design and Construction of the Aquaponic System

The constructed aquaponic system is shown in Figure 1. The components of the system are arranged in a logical manner to ensure that the desired air and water flow rates are maintained with optimal efficiency. Water effluent flows from the fish tank to the mechanical separator (radial flow) which reduces the water flow speed and allows for the sediments to accumulate at the bottom of the barrel for easy removal. This flow from the radial filter then flows to the bio-filter where the ammonia and nitrite excreted by the fishes in the fish tank are converted into nitrates by living bacteria contained in the bio-filter. Rakocy (2012) states that bio-filtration is essential in aquaponics because even low concentrations of ammonia and nitrite are toxic to fishes, while plants need nitrates to grow.

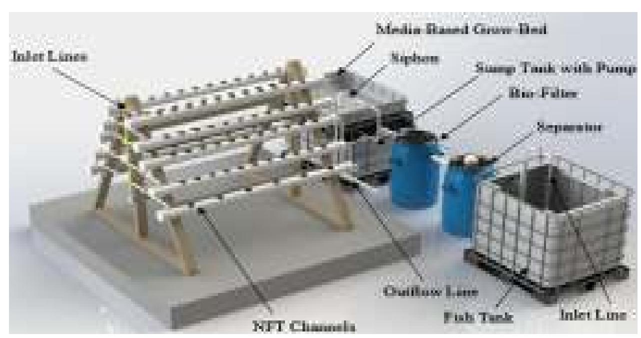


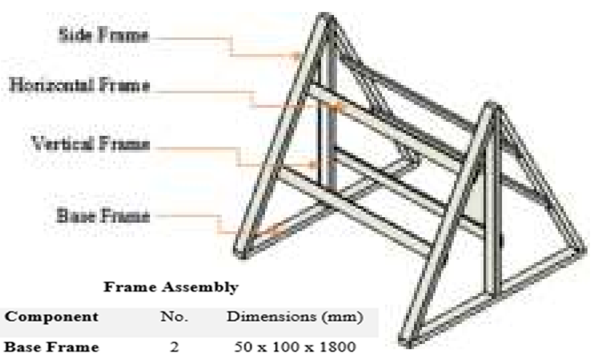
Figure 1. The Constructed Aquaponic Irrigation System

As the effluent from the fish tank flows through the radial flow separator and the bio-filter, it enters the sump tank where the pump delivers this nitrate rich water to both the media based grow bed and the NFT channels via 19 mm (¾ in) and 12.7 mm (½ in) diameter pipes respectively. The pump also simultaneously recycles this nitrate rich water to the fish tank via a 19 mm (¾ in) diameter piping network. The discharge from both the NFT channels and the media grow beds is recycled back into the sump tank, where a float mechanism maintains a steady water level to mitigate against water loss via plant uptake and evaporation. The siphon mechanism in the media grow bed also supplements the nitrification process as the expandable clay balls promote bacteria development which is needed to convert the nitrite components to nitrates.

The advantage of this design is that the inclusion of both mechanical and bio-filtration components allows for the fish load to be increased to satisfy a large plant sample, while ensuring the successful conversion of the ammonia content to nitrates. The vertical NFT system allows for the maximisation of the space for planting crops while ensuring the ease of use and friendliness of the system. Also, by having both the media base grow bed and NFT systems, the plant selection variety can meet the customer's requirement. This system seems efficient and each operation flows logically.

4. Details of the Construction

White pine wood 50 mm x 100 mm (2 in x 4 in), the most common type of wood, was used to build the frame of the system (see Figure 2). Additionally, 100 mm (4 in) diameter P.V.C pipes were used as the growing media channels (see in Figure 3) attached to the frames because it is lighter and easier to work with.



Frame Assembly

Component	No.	Dimensions (mm)
Base Frame	2	50 x 100 x 1800
Side Frame	4	50 x 100 x 2010
Vertical Frame	2	50 x 100 x 1800
Horizontal Frame	4	25 x 75 x 1800

Figure 2. Dimensions of the Various Parts of the Frame of the NFT System

Many hydroponic systems built in the past were also made from similar materials. In the NFT system, the length of the ten (10) growing media channels in the frame is 1.83 m (6 ft) and accommodates nine (11) plants (see Figure 3) each except for the two bottom channels which accommodate six (6) plants each, making a total of 100 plants (see Figure 4). Twelve (12) plant spots are specifically designed for large leafy crops such as lettuce or pak-choi. The remaining eighty-eight (88) spots are designed for herb type crops such as chives, celery, shadow benny and basil. The media grow bed, as seen in Figure 4, had 30 plants which can be either leafy crops or herbs, thus making the system have a total capacity of 130 plants.

Figure 3. Details of the Growing Media Channels in the NFT System

* - Expandable clay balls were used as the growth media.

Figure 4. Plants in the NFT (left) and the Media Grow-bed (right) Hydroponics Systems

The maximum holding capacity of the sump tank is 950 litres which was selected as the reservoir. The volume of the water at the tank, however, was maintained at 535 litres via a float mechanism that replenished water that was lost from a water tap. The size of the pump used for the whole system was 12 m^3/hr. For the system, an air flow of approximately 30 L/hr was required for the air pump in the media grow beds and this air flow rate would ensure that the oxygen levels stayed within 6-10 ppm range for the optimal growth of the lettuce, pak-choi and most leafy crops (Kuack, 2015). The dimensions of the fish tank were 1.02 m x 1.22 m x 0.76 m, giving a volume of 0.946 m^3 which is 946 litres. The recommended fish stocking density is 20 kg of fish for every 1,000 litre of water capacity (Somerville et al. 2014). The fish stocking density recommended was therefore 18.72 kg. Assuming that the average harvest size of tilapia is 0.5 kg, the maximum number of tilapia fishes to be held by the tank is 37 fishes. Due to the reproductive, sprawling and ammonia outtake behavior of the fishes, the system shouldn't occupy the maximum amount fish at the start of operations. Using 55% as the starting number, 20 fishes were selected.

5. Testing of the Constructed Prototype Aquaponic Irrigation System

The testing phase evaluated the water quality, fish and plant parameters. The water quality of the aquaponic irrigation (T_1) system was evaluated to ensure that the living organisms had an environment that promoted optimal living conditions. Plant parameters were measured to compare the growth performance of the plants in the urban aquaponic system with the conventional soil-based system (T_2) used by local farmers.

An API Freshwater Master Test Kit (API, 2018) was utilised for water quality monitoring. This test kit was used to measure pH, ammonia (NH_3), nitrites (NO_{2-}) and nitrates (NO_{3-}) levels in the fish tank. The test kit comprised of several glass vials for testing and colour charts for each test. A dissolved oxygen (DO) meter was used to deduce the DO levels in the water so that adjustments could be made if necessary, to ensure that the DO was always at an optimal level. These water quality parameters were tested for sixty-six (66) days. Readings were taken between 5-7 pm each day and every test was replicated twice. The ambient temperature in the fish tank was also measured.

There were 20 fishes in the fish tank. The fish length and weight were measured every two (2) weeks from the initial priming date of January 28, 2019. Unfortunately, two (2) tilapia fish died in the priming stage so the results would reflect data from 18 fishes with the system's fish survival rate (SR) being 90%. Using a fish net, a random fish from the fish tank was selected and placed in the scale's measuring bowl. The length of 3 fishes was then measured using a measuring tape from the fish's mouth tip to the end of its tail. The weights of the 3 fishes were also taken.

Hundred (100) plants of five crops: Pak choi, chive, bronze lettuce, ice berg lettuce and romaine lettuce were planted in the NFT system while thirty (30) plants of the celery crop were planted in the media grow bed (see Figure 4). Only the growth results for the first three named plants in the NFT system were reported since the values for the ice berg and romaine lettuce followed the same trend as for the bronze lettuce. Shoot diameter (with a Vernier calliper), plant height (with a ruler) and number of leaves of the plants in the aquaponic system (T_1) and the conventional soil-based system (T_2) were monitored in two (2) day intervals from the start of the planting stage which began on the 4th March, 2019 and this testing period lasted for four (4) weeks. The T_2 system comprised of two (2) 1.8 long channels in which soil was placed in it. Four (4) sets of readings were taken for each parameter.

6. Results

Table 1 shows the mean values of the measured water quality parameters in the fish tank. During the testing duration period, the mean pH value varied from 7.4 to 8.0 showing that there were no major differences of the pH values during the test period. Mathematically, pH is the negative logarithm of the hydrogen ion (H+) concentration, which means that the higher the pH value, the less free hydrogen ions would be present. The concentration of carbon dioxide CO_2 influences the pH of the natural water (Ekubo and Abowei, 2011). In this present study, the average pH value in the fish (7.72) and the range of values are well within the target pH ranges set in previous studies by many authors, like Somerville et al. (2014), for tilapia fish growth. There were only gradual decreases and increases in pH for the aquaponic system which is indicative of the nitrification process (EPA, 2002).

The mean water temperature of the fish tank was 28.03 ± 0.16 ^{0}C (see Table 1). The minimum and maximum water temperature were 27.4 ^{0}C and 28.7 ^{0}C respectively showing that there were no significant differences of the temperature throughout the testing period. Temperature affects the dissolved oxygen and ammonia toxicity levels. The temperatures measured in the fish tank were then within the temperature tolerance range of between 25.2 ^{0}C and 28.3 ^{0}C required for optimal growth of the fishes (Nelson, 2008).

Table 1. Water Quality Parameters in the Fish Tank

Days after testing began	**pH**	**Temperature (ºC)**	**Dissolved oxygen (mg/L)**	**Ammonia (ppm)**	**Nitrite (ppm)**	**Nitrate (ppm)**
0	7.4	28.6	8.6	0	0	0
7	7.8	27.5	8.3	0	0	0
14	7.6	28.3	7.8	0.25	0	0
21	7.4	27.8	7.6	0.25	0.25	0
28	7.8	27.6	7.8	0.25	0.25	5.0
35	7.6	28.4	7.4	0.50	0.25	5.0
42	7.8	27.4	7.4	0.75	0.50	5.0
49	8.0	28.6	8.5	0.50	0.25	10.0
56	7.8	28.7	7.6	0.50	0.25	10.0
66	8.0	27.9	8.4	0.25	0.50	10.0
Mean	7.72 ± 0.07	28.03 ± 0.16	7.94 ± 0.15	0.33 ± 0.08	0.23 ± 0.06	4.50 ± 1.38
Target level*	6.0 – 7.5	22.0 -32.0	> 5	< 0.25	< 0.25	5-150

*- Suggested by Somerville et al. (2014), for ideal fish growth.

It is showed in Table 1 that the dissolved oxygen levels maintained a relatively stable value over the study period which showed that the system was not affected by any significant algae outbreak or any factors that could have caused the depletion of the oxygen levels. Figure 5 illustrates the levels of ammonia, nitrite and nitrate (as detailed in Table 1) that was present in the system throughout the sixty-six (66) day testing period. The figure exemplifies the process of nitrification and validates this system's functionality. The ammonia content level remained low because the nitrifying bacteria converted it to nitrites and subsequently to nitrates which was then consumed by the plants. The nitrate level only started to rise in the 3rd week of the priming stage which was mainly as a result of the addition of beneficial bacterial in the fish tank at the start of the 2nd week.

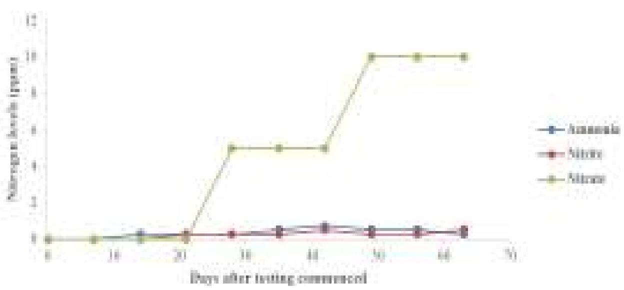


Figure 5. Nitrogen Levels in the Fish Tank During the Test Period

This addition of bacteria in the second week helped to develop the bacterial colony in the system which resulted in the ammonia being converted to nitrites at the start of week 3 as seen in Figure 5. After the 4th week of testing the system's nitrifying bacteria had colonised to an acceptable level as the nitrate levels started to increase gradually. The surplus of nitrates is not toxic to the fishes and indicates that more plants could be incorporated in the system. Hence, the fishes experienced a successful growth level within the nine (9) week testing period (see Table 2). Each fish grew an average of 0.05 cm every day with a daily weight gain of 1.48 g. This indicates that the fishes

Table 2. Mean* Fish Length and Weight during the Growth Period

Days after testing commenced	Fish length (cm)	Fish weight (gm)
0	15.32 ± 0.07	58.26 ± 1.08
14	16.13 ± 0.09	72.86 ± 2.80
28	16.57 ± 0.03	81.89 ± 1.25
42	17.26 ± 0.04	93.67 ± 2.64
56	18.37 ± 0.06	121.48 ± 2.43
66	18.85 ± 0.08	156.02 ± 4.84
Total gain	3.53	97.76
Mean daily gain	0.05	1.48
Percentage total gain	23.04	167.80

* - Mean of 4 values ± standard deviation

The plant growth performance (see Table 3) which was measured over a one-month period for the aquaponic and the conventional farming systems showed that the plant height, plant shoot and the number of leaves advanced more in the aquaponic (T1) system more than in the conventional farming (T2) system. The plant height of the pak choi plant was plotted for the two modes of farming in Figure 6.

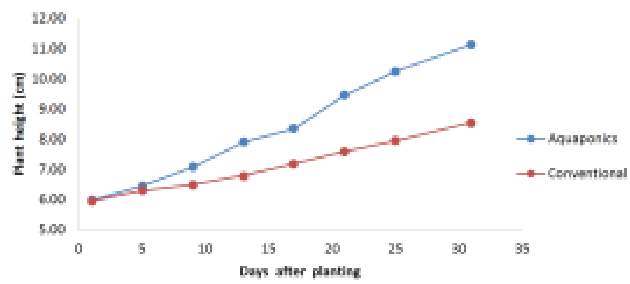


Figure 6. Plant Height for the Pak Choi Crop

were maintained in a healthy environment and received optimal conditions that promoted growth.

Results showed that both farming systems produced a growth pattern that showed a linear increase in the plant height over the testing period. Results showed that the heights of the plants in the aquaponic system advanced at a faster pace in comparison to the plants in the conventional farming system, which is evident from Figures 7 and 8. The parameters of all the crops followed the same trend as shown in Table 3.

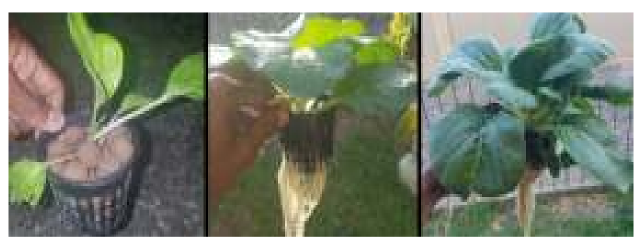


Figure 7. Pak Choi Development for T1 System during the 1st, 2nd and 4th weeks, respectively

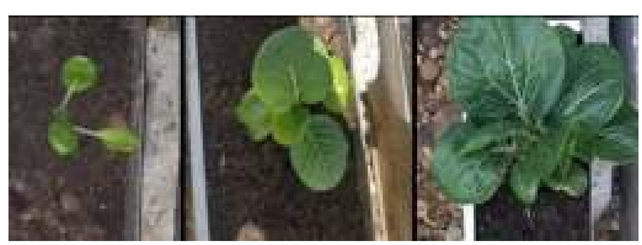


Figure 8. Pak Choi Development for T2 System during the 1st, 2nd and 4th Weeks, respectively

Table 3. Mean Values of the Plant Parameters in the Aquaponic and Conventional System

Days after Planting	Plant Height (cm)							
	Pak Choi		Chive		Calery		Bronze Lettuce	
	T1*	T2*	T1	T2	T1	T2	T1	T2
1	5.98	5.95	24.45	25.45	19.88	20.95	7.20	7.40
5	6.45	6.30	24.85	25.75	20.93	22.45	7.93	7.75
9	7.08	6.50	25.83	26.10	21.55	22.90	8.25	7.95
13	7.90	6.80	26.78	26.40	22.78	23.15	9.05	8.30
17	8.35	7.20	28.33	26.75	23.55	23.50	9.83	8.75
21	9.45	7.60	30.15	27.15	25.13	23.85	10.43	9.05
25	10.25	7.95	31.35	27.55	25.85	24.05	10.78	9.45
31	111.15	8.55	32.63	28.05	27.25	24.40	11.23	10.00
Days	**Shoot Diameter (mm)**							
1	0.41	0.42	0.42	0.43	0.23	0.24	0.51	0.44
5	0.46	0.45	0.47	0.45	0.27	0.25	0.57	0.47
9	0.54	0.47	0.53	0.48	0.34	0.27	0.64	0.49
13	0.69	0.50	0.61	0.51	0.43	0.31	0.74	0.53
17	0.80	0.54	0.66	0.59	0.44	0.35	0.79	0.60
21	1.13	0.57	0.72	0.63	0.58	0.37	0.84	0.63
25	1.40	0.62	0.75	0.68	0.65	0.43	0.96	0.68
31	2.10	0.70	0.83	0.81	0.76	0.49	1.11	0.74
Days	**Number of Leaves**							
1	5.75	5.50	5.50	6.00	4.25	4.00	8.00	8.00
5	5.75	5.50	5.50	6.00	4.25	4.00	9.75	8.50
9	6.75	6.50	5.50	6.50	4.50	5.00	12.75	9.00
13	7.75	6.50	5.50	6.50	5.00	6.00	15.75	9.50
17	8.00	8.00	5.50	6.50	5.50	6.00	19.25	10.50
21	11.25	9.00	7.25	7.50	8.50	6.50	19.75	12.50
25	12.25	9.50	7.25	8.00	9.75	7.50	21.25	13.50
31	15.75	11.50	8.00	8.00	12.50	8.00	21.75	15.00

* - Values for plants in the aquaponic system (T_1) and conventional soil-based system (T_2)

7. Discussion of Results

The urban aquaponic irrigation system provided satisfactory environmental conditions for the development of both the fishes and plants during the period analysed. The water quality parameters were within the optimal limits suitable for tilapia fish survival and plant development (Somerville et al., 2014). It was essential that this system would be compact and allow the user to have a high volume of plants with the space used. This was done by designing the system to occupy more vertical space with the utilisation of the NFT channels. Based on the research findings, most aquaponic systems rarely use the NFT component as the main avenue to grow plants due to the lack of filtration and pH buffering offered as compared to media bed and deep-water culture techniques respectively.

This constructed aquaponic design incorporated a rigorous filtration system that ensured that the usage of the NFT channels to maximise plant output and space could be achieved. This is where this system differed from systems previously built. The system includes both the mechanical and bio-filter filtration systems to ensure that the nitrifying bacteria had an environment to completely break down the ammonia output from the fish waste by having the water flow subjected to both filters. The design of this system allows for easy expansion if needed in the future as the system's NFT channels could be easily joined to increase the system's plant capacity. This system has an excess of nitrate level so an increase in the plant capacity in the future can be facilitated without comprising the uptake of nutrients and flow rate of the water.

The alkalinity of the water was found to be 7.72 ± 0.07 which was within the 6.0-8.5 range needed for ideal fish development (Ekubo and Abowei, 2011) and within the target pH ranges for the uptake of nutrients by the plants. Although the mean pH value is of the higher end of the target range for the plants, the pH levels were managed and controlled with the assistance of the natural pH stabiliser of the expandable clay balls in the media-grow bed and the NFT Channels. The nitrite level ranged from 0 - 0.5 ppm with a mean value of 0.23 ± 0.06 ppm. Heterotrophic bacteria facilitate the capture of ammonia and their transformation into microbial protein, whereas the autotrophic bacteria allow for the oxidation of ammonia to nitrites and nitrates (Ebling et al., 2006). It is evident from the ammonia levels (see Table 1 and Figure 5) that heterotrophic bacteria promoted the decomposition of the organic matter and reduced the total ammonia nitrogen levels.

The higher shoot diameter, plant height and number of leaves of the plant crops observed in the aquaponic system in comparison with the conventional soil-based system showed the possibility of better performance and productivity from the aquaponic system. The aquaponic system did not just outperform the conventional system in terms of growth performance, it also provided advantages over the conventional system since it allowed for the optimisation of the system's resources to benefit two cultures, both plant and fish. The performance data of plant growth (see Table 3) proved that the non-usage of pesticides in the aquaponic system did not affect the performance of the plants, as they were not susceptible to any pests in the first instance. The conventional soil system utilised chemical fertilisation as the soil in most cases do not possess the required nutrient levels, however this aquaponic system produced organic produce which was a main requirement of the customer needs.

This aquaponic system was designed for residential usage (such as backyard usage and around schools etc.), but this system can easily be expanded via the NFT channels to convert its function to commercial output if desired in the future. This system could also be used for educational purposes in schools as it would show case the organic side to producing crops and would allow students to witness the plant's performance on a daily basis. This system would only help to encourage students to pursue a career in agriculture and would help to negate the cultural beliefs that the agricultural sector cannot produce high paying jobs. This mind changing policy would only serve to assist the nation's food importation bill in the long term.

The economical side of the system shows that the aquaponic irrigation system is relatively cheap with an estimated material costing of US $730.00 and based on present labour pricing by experts, the labour costing to manufacture this system would be in the range of US $120-180. This would give a total cost of about US 880.00 which is reasonable when one considers the returns on the investment. This system can hold approximately 130 plant crops and using a lower limit price for each plant crop of US $1.50, this system can generate $195.00 within six weeks. This return would also be supplemented with the money to be derived from the fish when it fully matures.

8. Conclusion

The urban aquaponic irrigation system was successfully designed, manufactured and tested. The testing data showed that the objectives of this project were achieved. The nice growth performance achieved showed that this system provided adequate conditions for fish and plant growth. The ammonia levels and water quality parameters of the system were vigorously tested to ensure the values were within the stipulated target range for a healthy system.

The aquaponic system worked at a desirable level and this system can be interpreted as another step taken to make Trinidad and Tobago's agricultural sector more sustainable and less vulnerable to environmental shocks.

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DIALux Capabilities with Planning of LED Lighting Solutions: Some Findings in Trinidad and Tobago

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Abstract: *Light emitting diodes (LED) is energy efficient, long lasting and environmentally friendly but is not widely used as compared to traditional lighting. This study aimed to investigate the current challenges and issues faced in adopting LED lighting in projects, and to show cases how the DIALux system could be utilised for generating viable lighting solutions in Trinidad and Tobago (T&T). This paper reviews the concepts of LED lighting solutions and the factors affecting LED adoption in lighting projects. It then relates the challenges of LED adoption, and explores suitable lighting solutions using DIALux, in projects of both public- and private-sectors in T&T. For exploring the DIALux capabilities for generating LED lighting solutions, projects of varying nature were selected and then diagnosed with the DIALux system. Compared to traditional lighting, LED lighting has superior qualities in various ways such as being energy efficient, has a long lifespan, durable, and is environmentally friendly. It was found that industry practitioners lacked the knowledge of adopting LED lighting. From the analysis of the selected lighting projects, DIALux could rectify issues in determining the number of lighting, the style of lighting and the installation position of the lighting. The system could also be useful to do simulations on areas that need lighting. Using the efficient and effective LED lighting with DIALux could keep the energy requirement minimum, whilst achieving the lighting design objectives. Adopting DIALux could generate useful results at the planning stage of lighting projects. Future studies should focus on assessing among the dominating factors of LED lighting adoption and the applicability of DIALux in planning and executing lighting solutions.*

Keywords: *Light emitting diodes (LED), DIALux system, lighting projects, Trinidad and Tobago*

1. Introduction

Lighting plays a vital role in the workplace because having the correct lighting in an area helps keep the mind alert, and improves concentration which helps in a healthy attitude to work (Ahmad, 2013). Energy consumption in buildings has increased because of the increasing demand for ventilation and air conditioning and lighting in buildings. Energy efficiency means using less energy to provide the same service. Ahmad (2013) contended that efforts have been put towards reducing the demand for energy through energy efficient designs. Hence, high quality lighting design includes the coordinated selection of lighting, fixtures, and installation. This process can face different challenges at various phases (Ahmad, 2013; Ramrose, 2019).

Light emitting diodes (LEDs) are being used increasingly to provide lighting solutions for domestic and commercial lighting. For instance, the US Environment Protection Agency has calculated that LED lights would save 88 terawatt-hours of electricity from 2010 until 2030 – enough to power seven million homes for an entire year (Writer, 2017). Similarly in Britain, it has been calculated that the country as a whole could save GBP1bn in energy bills every year – the equivalent of GBP50 per household – simply by switching to LEDs, and save around 5 million tonnes of carbon dioxide annually (Customer Education, 2014). Even reducing this number by a tiny percentage, it would have a positive effect for the country's green economy. In Trinidad and Tobago (T&T), it has considerably increased the energy consumption. Many projects require a lot of lighting sources in both public and private sectors. Energy efficiency practices are greatly increased due to the issues with climate change and high energy pricing (Edirisinghe, 2012). Unfortunately, a lot of projects in T&T use lighting systems that are not suited for the environment and the economy (Ramrose, 2019). Records showed that the amount of imported fluorescent lamps during the period of January 2011 to August 2016 was 8.2 million fluorescent bulbs. This would have resulted in high amounts of mercury entering the environment when these bulbs are eventually disposed of (Batchasingh, 2016).

LED lighting solutions could offer potentially large savings in the energy and the environmental sectors. Nevertheless, traditional lighting has mostly been using in preference to LED lighting in T&T. According to a recent study undertaken in 2019 (Ramrose, 2019), many industry practitioners have been aware of the need to improve the lighting efficiency by adopting efficient LED lighting in projects in both private and public sectors. However, the 'right' application (with number of LED lighting) would not always be used. Many companies would not use LED lighting as they perceived high costs of and/or lacked the knowledge on the benefits of LED lighting.

It has been realised the importance of energy efficiency practices and a need to select the 'right' application of LED lighting in projects. The use of computer software has been impacting the building design and helping the engineers and clients to choose amongst the feasible solutions of the lighting projects while reducing energy consumption (Davoodi, 2016). One of main software used is the DIALux software which is being used to design the lighting for indoor and outdoor (Dial, 2019; Airfal, 2019). In this context, this paper reviews the offers of LED lighting solutions and the DIALux software, and discusses the factors and barriers of LED adoption in lighting projects. By analysing the LED lighting application cases with the use of DIALux software in both public and private projects, this paper aims to explore the DIALux capabilities with planning of LED lighting solutions and projects in T&T. This paper also provides recommendations for future work.

2. LED Lighting Solutions and the DIALux Software

A light-emitting diode (LED) is a semiconductor light source that emits light when current flows through it. Electrons in the semiconductor recombine with electron holes, releasing energy in the form of photons (Wikipedia, 2019a). The colour of the light (corresponding to the energy of the photons) is determined by the energy required for electrons to cross the band gap of the semiconductor. White light is obtained by using multiple semiconductors or a layer of light-emitting phosphor on the semiconductor device (Edwards, 2019).

Appearing as practical electronic components in 1962, LEDs have been and are used in applications as diverse as aviation lighting, automotive headlamps, advertising, general lighting, traffic signals, camera flashes, lighted wallpaper, horticultural grow lights, and medical devices (Peláez and Villegas, 2007). The circuits used within the LED lighting bulbs vary from one manufacturer to the next (Electronics Notes, 2019). Although LED lighting technology involves more electronics and in many respects can be more complicated than other forms of lighting, the cost of LED lighting is falling to the extent where it has become much cheaper when the expected lifetime for the light and the energy usage are considered (Electronics Notes, 2019).

In recent years, there has been a significant move to use LED technology for general lighting. LEDs introduce new opportunities for changing the hue of light and its brightness with a simple switch (Edirisinghe, 2012). Table 1 provides a list of advantages versus disadvantages of LED lighting. As compared to traditional light sources (like incandescent, compact fluorescent lights, compact fluorescent lamps (CFLs), tungsten, sodium, and other forms of lighting), LED lighting is more energy efficient, has a longer lifetime, has less maintenance requirements, uses no mercury, and contributes to reduced climate control costs. It reduces heat and ultraviolet (UV) emissions, and the devices contain no mercury (Electronics Notes, 2019; Ramrose, 2019).

Nowadays, LED lighting solutions have become one of the most cost-effective products as they are energy efficient (UN Environment, 2017). Several lighting design software (e.g., DIALux, AutoLUX, RELUX, Ulysse, and Calculux, etc.) were developed and have been using for analysing photometrics, building information modelling

Table 1. Advantages versus Disadvantages of LED Lighting

Advantages	Disadvantages
• ***Colour***: LEDs can emit light of an intended colour without using any colour filters as traditional lighting methods need. • ***Cool light***: In contrast to most light sources, LEDs radiate very little heat in the form of IR that can cause damage to sensitive objects or fabrics. • ***Cycling***: LEDs are ideal for uses subject to frequent on-off cycling. • ***Dimming***: LEDs can very easily be dimmed either by pulse-width modulation or lowering the forward current. • ***Efficiency***: LEDs emit more lumens per watt than incandescent light bulbs • ***Focus***: The solid package of the LED can be designed to focus its light. • ***Lifetime***: LEDs can have a relatively long useful life. • ***Shock resistance***: LEDs, being solid-state components, are difficult to damage with external shock. • ***Size***: LEDs can be very small (smaller than 2 mm^2) and are easily attached to printed circuit boards. • ***Slow failure***: LEDs mainly fail by dimming over time, rather than the abrupt failure of incandescent bulbs. • ***Warmup time***: LEDs light up very quickly.	• ***Area light source***: Single LEDs do not approximate a point source of light giving a spherical light distribution. • ***Colour rendition***: Most cool-white LEDs have spectra that differ significantly from a black body radiator like the sun or an incandescent light. • ***Efficiency droop***: The efficiency of LEDs decreases as the electric current increases. • ***Impact on wildlife***: LEDs are much more attractive to insects than sodium-vapour lights. • ***Light pollution***: White LEDs emit shorter wavelength light than sources such as high-pressure sodium vapour lamps. • ***Temperature dependence***: LED performance largely depends on the ambient temperature of the operating environment – or thermal management properties. • ***Thermal runaway***: Parallel strings of LEDs will not share current evenly due to the manufacturing tolerances in their forward voltage • ***Use in winter conditions***: LED lights used for traffic control can have snow obscuring them, leading to accidents. • ***Voltage sensitivity***: LEDs must be supplied with a voltage above their threshold voltage and a current below their rating.

Source: Abstracted from Wikipedia (2019a)

(BIM), and 3D modelling (Wikipedia, 2019b). DIALux is a free software developed by DIAL for professional light planning (Dial, 2019; Airfal, 2019). The software is available as a desktop version and as a basic mobile app, and is used by importing the structural design via CAD/image files. The lighting elements are inserted, and the lighting objects are associated with a photometry via IES (Illuminating Engineering Society) files (i.e., file format for photometric data). The photometry of a light fixture describes the way it distributes its light into space. Once this process is completed, the illuminance and luminance produced by each fixture in the space can then be calculated. The output would typically be a diagram indicating these by means of colours or numbers (Wikipedia, 2019b; Dial, 2019).

For marketing and higher-level design, 3D photometric analysis is useful to give a graphical output of a proposed design (Wikipedia, 2019b). Being a platform and tool, the DIALux programme is a typical lighting design software that connects planners and manufacturers. Edirisinghe (2012) argues that the LED lighting is constantly developing new methodologies and technologies that could be utilised into lighting designs and practice. With the aid of lighting design software (such as, DIALux), it could be used to rectify issues on determining the number of lighting, the style of lighting and the position of the lighting (Ramrose, 2019).

3. Factors Affecting LED Adoption in Lighting Projects

There is a growing need for efficient and inexpensive lighting due to the energy prices increasing and an increased interest in sustainability. High efficiency, environmentally friendly lighting is needed. Such need can be met effectively with LED lighting due to recent advances in LED technology and production techniques (Thorpe, 2012; Ramrose, 2019). Figure 1 illustrates various factors that would have impact on the adoption of LED lighting technology in projects. These factors are elaborated, as follows:

1) *Brand* - The brand of an item portrays name, logos, symbols, awareness, and association. Creating brand awareness for LED can always pose a challenge, as brands affect the customers' choice when purchasing (Leelakulthanit, 2014).
2) *Compatibility with Existing Fixtures* - One major block for adopting LED in lighting projects is the incompatibility of LED fixture to the existing fixture, transformer or the dimmer. The incompatibility could be mechanical in nature, or of thermal or electrical issues (Leelakulthanit, 2014).

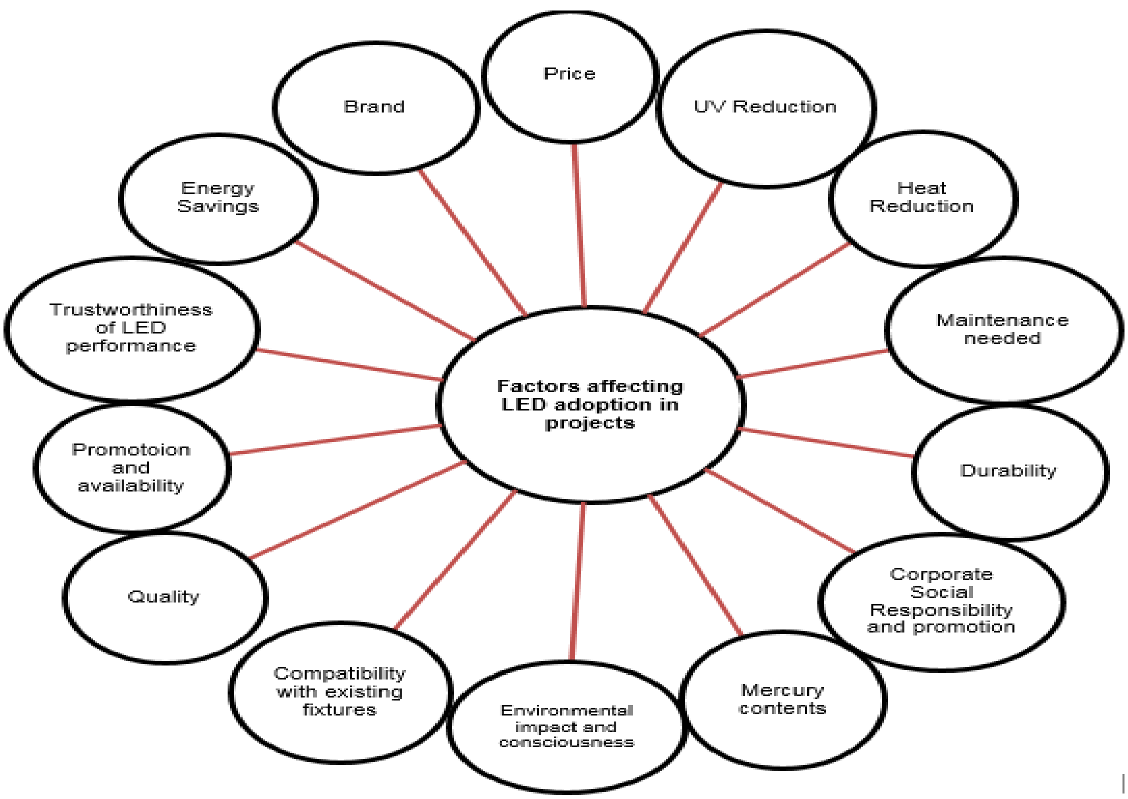

Figure 1. Factors Affecting LED Adoption in Projects
Source: Abstracted from Ramrose (2019)

3) *Corporate Social Responsibility* - Companies integrate social and environmental concerns in their business operations and interactions with their stakeholders. This image would gravitate customers towards the business to purchase LED lighting (Leelakulthanit 2014).
4) *Durability* - LED emits 70% of its initial light output and last longer than traditional lighting (Glamox, 2018). LED lighting lifespan is 50,000 hours. This means that there is the fewer need to replace a LED bulb, and thus a better return to the consumer as compared to the high initial investments.
5) *Energy Savings* - The circuit of LED lighting will approach 80% efficiency which indicates that 80% of electricity is converted to light energy, while only 20% is lost as heat. The savings in energy would motivate practitioners to adopt LED lighting in projects (Kendall, 2017; Energystar, 2018).
6) *Environmental Impact and Consciousness* - People are being more environmentally conscious. This result in greater ecological consciousness and the favouring of companies that promotes and support environmental practices, and the desire to purchase eco-friendly products, including LED lighting (Laroche et al., 2001; Biswas et al., 2000).
7) *Heat Reduction* - LEDs use heat sinks to absorb the heat produced and then dissipate it into the surrounding environment (Lambert, 2017). LEDs are able to use light and energy more efficiently in a multitude of applications (Energystar, 2018; Ahmad, 2013).
8) *Maintenance Requirements* - LED lighting lasts longer and has little flickering issues as compared to traditional lighting (Glamox, 2018). It is low maintenance, and therefore little or no money is spent ensuring they last longer once installed.
9) *Mercury Content* - Mercury is detrimental both to environment and human health (US EPA, 2018). LED lights contain absolutely no mercury whereas fluorescent lamps operate at a very low gas pressure, when an electric current passes between two electrodes in a tube filled with low-pressure mercury vapour that produces light (IMERC, 2014).
10) *Price* – The LED products would save the consumer money over the long term. However, higher initial cost of the LED lighting would hinder its adoption in projects as compared to that of the traditional lighting (Leelakulthanit, 2014).
11) *Promotion and Availability* – Promotions of LED products would allow new buyers to be attracted, to reward loyal clients and to encourage current customers to repurchase (Leelakulthanit, 2014). Hence, if LED lighting is inadequately available and the marketing of its environmentally-friendly nature is not emphasised, this would prevent projects from adopting LED lighting.
12) *Quality* - There are many physical and physiological attributes (such as, luminance uniformity, luminance distributions, light colour characteristics and glare) that can influence the perception of lighting quality (Edirisinghe, 2012). LED lights are resistant to vibration and shock, and operate effectively in hot and cold environments. They last longer than traditional lighting as LED bulbs do not burn as fast as incandescent bulbs (Leelakulthanit, 2014).
13) *Trustworthiness of LED Performance* - Research suggests that consumers tend to not trust the claim that products are “green”, and therefore this hinders their actual purchase (Mostafa, 2009). Many customers lack experiences with LED products and only have the information from company advertising or referrals from friends and family (Mostafa, 2009).
14) *UV Reduction* - Different types of UV radiation are emitted by respective types of light bulbs currently available on the market (Colleen, 2016; Burnham, 2012). LED lighting produces a very small amount of UV radiation due to the phosphors within an LED lamp that converts the UV light to white light. This is a promoting factor of LED lighting.

4. Technicalities of LED in Lighting Projects

There has been a lack of technicalities and knowledge on LED capabilities that would lead to making wrong decisions on lighting solutions for any project (Ramrose, 2019). These technicalities include:

1) *Installation* - Installation design for good energy usage begins by ensuring that lighting is not spread unnecessarily (Ahmad, 2013). If one is not aware of how a LED light should be installed, in particular what height, this can cause disturbance to the user.
2) *Glare* - If a light is installed and it is too bright, glare will affect visibility which can result in one being uncomfortable (Ahmad, 2013). Selection of the wrong type of LED lighting can lead to disturbances as each light is designed for a particular environment.
3) *Uniformity* - The flickering of a light can affect the user by creating annoyance or even headaches (Ahmad, 2013). LED lights may flicker if the chips are burnt out or if the driver has failed. This possesses a great challenge as some projects may have lost work time depending on the type of lighting used and the height it was installed.
4) *Ballast* - In order to replace the fluorescent with LED lighting, the ballast must be removed and the fixture must be rewired (Ahmad, 2013). Additional man hours are needed to have this done if there are projects that have already installed fluorescent fixtures and are converting it to LED.

5) *Colour Rendering Index* (CRI) - Colour rendering relates to the way objects appear under a given light source. The measure is called the "colour rendering index" (or CRI) (Ahmad, 2013). If the user is not knowledgeable on what he/she requires and selects the wrong CRI for the area, then the entire area may not appear as natural as it should.
6) *Illuminance* – It refers to the luminous flux density at a surface measured in lumens per square metre (lm/m^2) or Lux (lx) (Kumar and Choudhury, 2014). This is a specified level for visual task areas, which is important as it affects how well people can see what they can do and also how visual comfortable they feel. In addition, spaces with higher quality lighting would require less illumination (Ahmad, 2013).

5. A Study of the DIALux Applications on Lighting Projects in T&T

5.1 Design and Setting up of the Study

In T&T, there has been lacking of standards or policy put in place to increase the adoption of LED lighting. Traditional lighting is preferred attributable to cost factors and the lack of knowledge about LED lighting and solutions. (Ramrose, 2019). An attempt was made to explore suitable solutions using DIALux in both private and public lighting industry sectors in T&T. Invited lighting practitioners expressed different challenges when adopting LED lighting in their projects. For instance, many of them have not been aware of how many fixtures that could suit accurately to light an area, and have no knowledge if the wattage and style of light chosen would be of the right fit.

Based on the lighting data provided by practitioners in line with respective project specifications, a total of four (4) lighting projects were selected, comprising two (2) public cases and two (2) private cases. Table 2 provides a list of four projects that were looking for the suitable lighting design before proceeding to the implementation phase. These projects were to demonstrate how the DIALux system had been utilised for generating viable lighting solutions. Using the acquired data of respective projects, a Value Engineering (VE) job plan was guided with the analysis.

Table 2. Projects Selected for DIALux Testing

Public Projects (Tenders)	Private Projects
1. The supply of one hundred and seventy (170) light emitting diode (led) luminaires for Curepe interchange	3. The lighting up of a T&T Company Car Park
2. The supply of one hundred (100) double gooseneck decorative poles with LED luminaires for Tobago	4. The lighting up of a local Grocery

Value Engineering (VE) seeks the most favourable solution that would prevent any unnecessary cost (Tosca, 2018), and the VE analysis and modelling had been advocated for lighting projects in many recent studies with recorded success (e.g., Davoodi 2016; Iturbide-Jimenez et al., 2016; Kendall, 2017). Figure 2 shows the basic VE methodology used in the phase of the product design and development process.

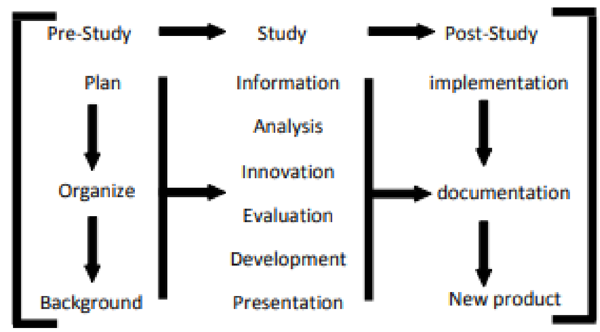

Figure 2. Lighting (Product) Design and Development Process
Source: Abstracted from Iturbide-Jimenez et al. (2016)

The various steps of the VE job plan used for this study are depicted, as follows:

1) *Information Step*: Information is to be gathered from the project practitioners and/or clients. This include, for instance, such as specifications, standards, and demands/needs (e.g., the layout, installation and maintenance conditions);
2) *Analysis Step*: Information and requirements of project are to be analysed and the functions to be diagnosed. This would address the required lux with conditions (like quantities, colour and furnishing), the luminaires, lighting system and sources and the controls needed to increase comfort and improve energy usage.
3) *Creative Step*: Ideas are to be generated in different ways to accomplish the required function needed from the light, which is what lux or how many fixtures needed, even the style or wattage;
4) *Evaluation Step*: Synthesise the ideas and concepts and select the most suitable lighting design with the DIALux lighting system. Financial evaluation is to be made by calculating the entire life cycle cost from the investment to operation to maintenance and a Function/Cost Analysis is done to ascertain the purpose(s) and determine value versus cost of the lighting solution.
5) *Development Step*: Select and prepare the best alternative for improving value, where the correct amount of fixtures is chosen, the position of each light is determined and the most appropriate style and wattage is selected to achieve the needed lux value; and
6) *Presentation Step*: Document the results of lighting analysis, solutions and recommendations and

present them to stakeholders (e.g., project practitioners and clients). This entails documentation where the selected lighting solution prepared to include installation drawing, control and assembly instructions as well as the list and amount of lighting needed to achieve the objective(s).

5.2 Analysis of Lighting Project Cases Using DIALux

Case 1: LED luminaires for Curepe Interchange

This Case was concerned with the supply of one hundred and seventy (170) LED luminaires for Curepe interchange in T&T. Figure 3 shows the site plan. The tender specified the street lights design and what quantity must be used. The aim was to determine if the 170 pieces of street light were sufficient to have the area well lit as it was required a lux of 28-32. Based on the data provided with the project specifications, the DIALux programme generated a solution that could determine the lux to light the entire area. Figure 4 shows the DIALux reading with a lux of 30 where most of the areas showing 'white' indicate that the project could proceed with its 170 pieces of street light (Ramrose, 2019).

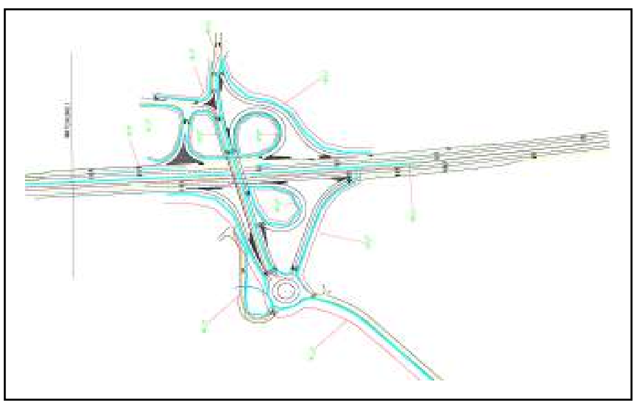

Figure 3. Site Plan at Curepe Interchange

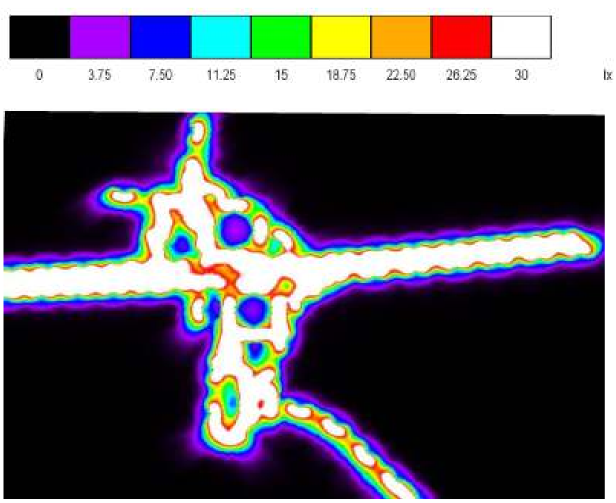

Figure 4. DIALux Colour-coded Result for Case 1 (Lux Values)

Case 2: LED Luminaires for Tobago

The second case dealt with the supply of one hundred (100) double gooseneck decorative poles with LED luminaires for Tobago. The practitioner would like to have advice on how an area could be lit to show the amount of brightness that the area would have and what was the best spacing option. The tender provided the lighting specification and the quantity. Since there was no site plan submitted, a DIALux was done for 4 light poles to give a sample view of what would be seen as shown in Figure 5. This lux coloured diagram helps the client see which areas are bright according to the colours, and Figure 6 indicates the lux values that can be obtained in each spot if the light is spaced 10 metres apart. Therefore, the DIALux provides assistance in an accurate spacing between light poles in this case (Ramrose, 2019).

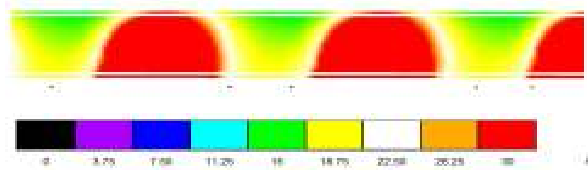

Figure 5. DIALux Result for Case 2 (Lux Values)

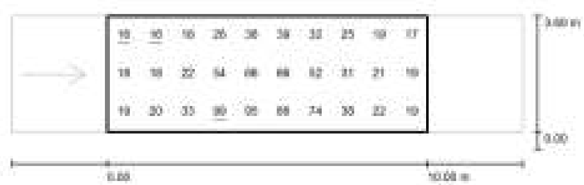

Figure 6. DIALux Result for Case 2

Case 3: T&T Company Car Park

The Case 3 was a project for lighting up of a car park for T&T Company (a fictitious name). The practitioner provided the exact size of the car park only, no AutoCAD drawing of the car park was provided. They needed to have the area well lit to ensure employees and customers can access their cars safely at night times. They did not know what type of lights or how many they would need, but the solution had to be economical as they had a fixed budget. They also needed to know where each light should be positioned. The client only provided the size (100 x 200m) of the area and no other information. The size of the area is drawn into the DIALux shown in Figure 7.

For this type of car park, Völlner 400W flood lights were recommended. The DIALux was used to test this. The amount of lights needed around the perimeter of the car park to ensure a lux of 50-60 as seen in Figure 8 is 18 pieces. Figure 9 provides the lux values at each point to confirm that the area is well lit, and Figure 10 shows a summary of result where the exact position of each light was determined (Ramrose, 2019).

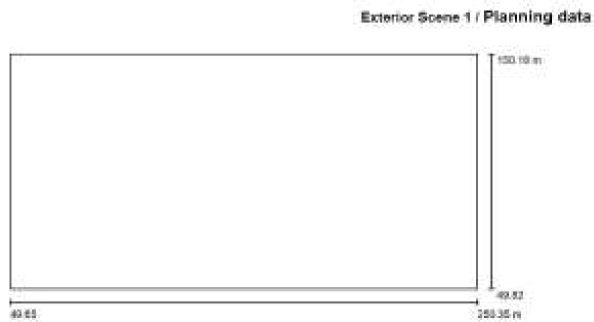

Figure 7. Site Dimensions of **T&T** Company Car Park

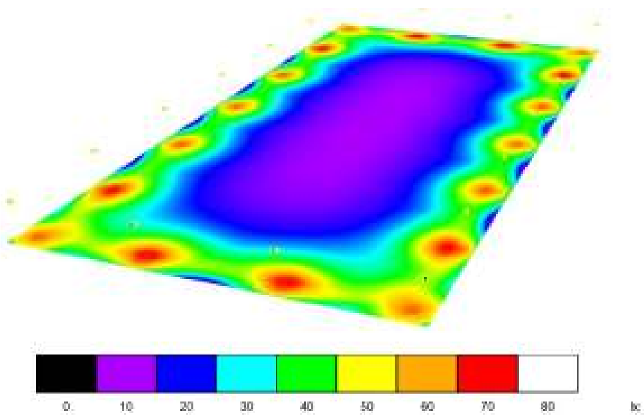

Figure 8. DIALux Result 1 for Case 3

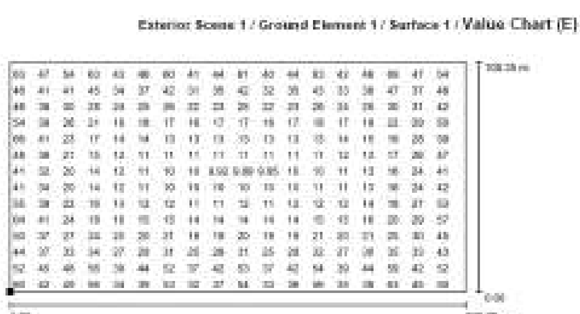

Figure 9. DIALux Result 2 for Case 3

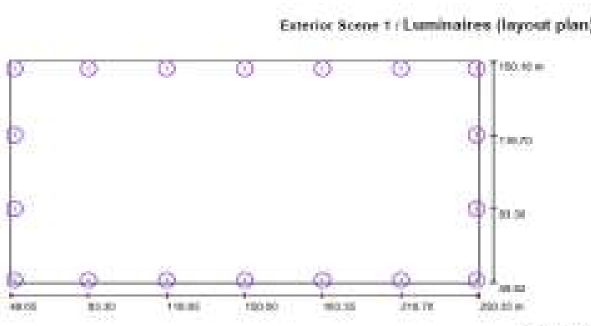

Figure 10. DIALux Result 3 for Case 3

Case 4: Trinidad Grocery Company

Case 4 involved Trinidad Grocery (a fictitious name) where the size of the area (the area - 80 x 14ft) for this project was provided. The practitioner wanted two different options of lighting, and the decision was based on price to purchase the lights and the price to install the lights. First option used 24 Völlner Quattro linear shown in Figure 11 which has a low wattage and is cheaper as well. Figure 12 shows how the 24 pieces of lights (4ft Völlner Quattro Linear Light) should be positioned.

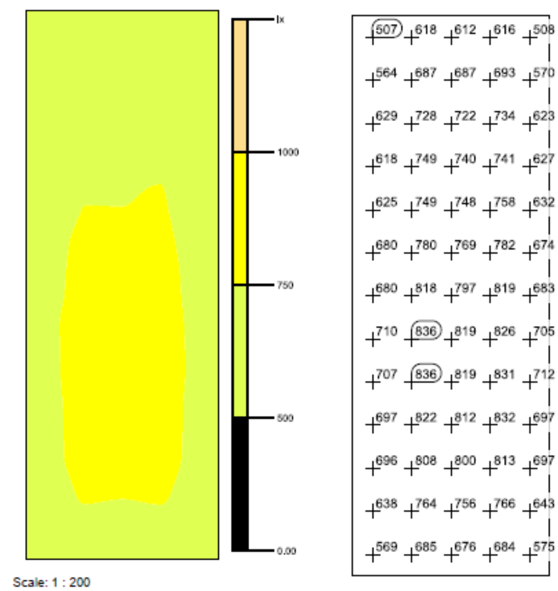

Figure 11. Lux Report for Case 4

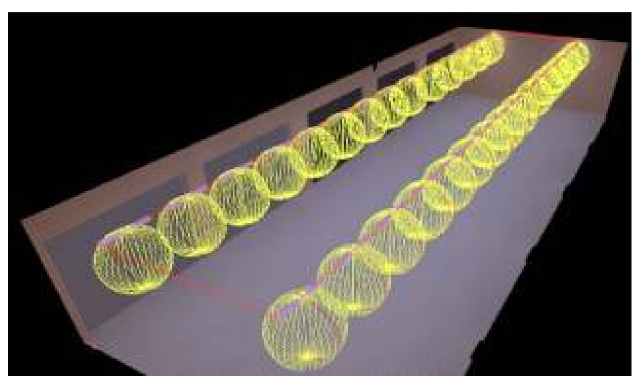

Figure 12. Position of Each Light Case - Option 1

The second option used 4 Völlner linear Highbay (4ft Vollner Quattro Linear Light) shown in Figures 13 and 14 which has a high wattage and also more costly, as compared to the Quattro linear. Figure 15 indicated the exact position the light should be installed. The 2 options could achieve similar lux or foot candle value. Based on the DIALux analysis, Option 1 was cheaper but has a lot of lighting to install with a high cost of labour. For Option 2, the lights would be more costly but there were only 4 lights to install with a much lower labour cost. In this regard, the DIALux could assist the practitioner in making the most suitable decision based on quantity, cost and labour (Ramrose, 2019).

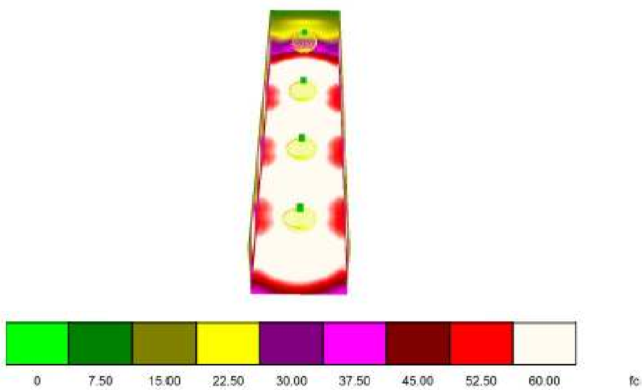

Figure 13. Option 2 DIALux Report - Case 4 Colour-coded

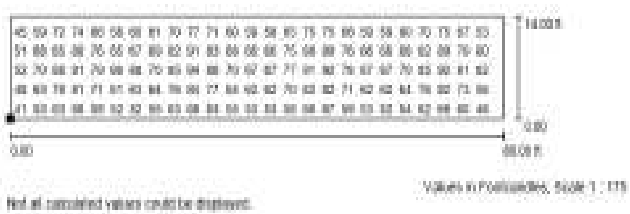

Figure 14. Option 2 DIALux Report

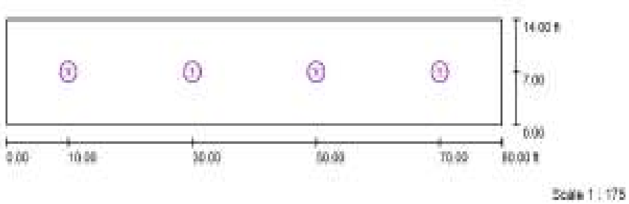

Figure 15. Option 2 Position of Lights for Case 4

5.3 Case Implications and Suggestions

With the aid of DIALux, lighting data of four respective projects were diagnosed, and the factors affecting LED verses traditional lighting were identified. The present status of the application of LED lighting is that either it is not being used at all or if it is being used, the wrong application is installed. Companies are not implementing it correctly due to the lack of proper tools and methods that should be used before the actual purchasing of lighting for a project. In addition to that, the practitioners in these cases also lack knowledge of LED lighting and therefore are not aware of its long-term benefits.

Another concern is that there is no enforcement of using LED lighting which should be preferred over traditional lighting since it is more environmentally friendly. The major barriers such as the lack of policies to increase the use of LED, the lack of awareness of LED benefits, the unfortunate market of poor quality LED that is present, have been focused on to either eliminate or reduce the impact of these barriers.

As evidenced from these lighting project cases, the DIALux programme generated the LED lighting solutions with agenda and action plan for implementation. It could provide the accurate type, number and style of LED lighting needed, and help with the selection of the best possible alternative to light an area with the lowest cost (Ramrose, 2019). Industry practitioners and clients should be made aware of the usefulness of the DIALux system. When proposing to them what light to use, this should be referenced with the DIALux report. The DIALux software handles the repetitive work on getting the 'right' lighting solutions for purposes. DIALux applications should be analysed and LED lighting solutions and cases could show benefits and economical savings to practitioners and clients.

In order to encourage the use of LED lighting, DIALux could be introduced and be a crucial step in the planning phase of a project before a decision is made to purchase any lighting. Another initiative is to develop some sort of standard that would help persons identify what is high quality LED lighting as well, so when clients do purchase the LED lighting they would not be disappointed by any failures of poor quality lighting. In order to increase the adoption of LED lighting in projects, a policy should be developed to assist projects across the country. Cost-benefit analysis must be done after the DIALux results are obtained to show the client what they were initially going to buy to what it should be. This is a great way to show physically how much cost can be cut before the actual installation of any lighting.

7. Conclusion

LEDs have many advantages over traditional light sources, including lower energy consumption, longer lifetime, improved physical robustness, smaller size, and faster switching. Driven by rising energy costs, LEDs are recommended due to its long lifetime, its energy efficiency, environmental benefits and lack of mercury content, and also its ability to operate at high and low temperatures, and emit low UV radiation levels (Juntunen, 2014).

This paper discussed the various barriers and technicalities faced in adopting LED lighting in projects in T&T. There has been no policy enforcing the use of LED lighting in projects. In addition to a lack of knowledge of LED benefits, many industry practitioners in T&T do not possess the expertise in what kind and what quantity of LED lighting should be used in the project. Cost misconception also poses another barrier as the cost to buy these LED lighting is higher than buying traditional lighting.

In order to attain the quality delivery of lighting projects while reducing cost, solutions generated from DIALux were explored. Based on the findings from diagnosis of four selected LED lighting projects in T&T, DIALux could rectify issues in determining the number of lighting, the style of lighting and the installation position of the lighting. Besides, the DIALux system could do simulations on areas that need lighting.

Future studies should focus on areas and dominating factors of LED lighting adoption in projects and the use of DIALux in planning and executing lighting projects. These include, for instance:

- Exploring the LED lighting solutions with use of sensors in lighting projects.
- Testing the amount of heat being released by LED lighting in an air-conditioned room as compared to other lighting.
- Analysis of indoor light versus outdoor light markets using LED separately. For example, outdoor lighting cost barrier is significantly higher than indoor lighting as it is cheaper depending on the features needed.
- Analysis of LED's potential effects on energy and carbon dioxide (CO_2) emissions with varying occupancy and equipment scenarios, and
- Conduct users' behavioural analysis with LED lighting, e.g., its effects of the circadian rhythm.

This paper demonstrates that adopting DIALux could generate useful results at the planning stage of lighting projects. Using the efficient and effective LED lighting with DIALux could keep the energy requirement minimum, whilst achieving the lighting design objectives. A recommendation is to integrate project management practices, where the DIALux is done in the planning phase of a project.

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Determining Thermal Characteristics of an Oil-Fired Crucible Furnace Using Clay and Alumina Bricks

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Abstract: *This paper explores the results of an experimental study that was intended to determine the thermal characteristics of an oil-fired crucible furnace using clay and alumina bricks. For the study, a refractory with 0.03118m^3 combustion chamber capacity was used. The bricks analysis were carried out under transient condition that would be appropriate for laboratory and workshop with a capacity to reach 950ºC within 20 minutes for aluminum and nonferrous scrap re-melting. The performance of the furnace was evaluated, and the results showed that the furnace can operate at a heating rate of 49.44°C/min, with a 29.70% efficiency determined, and which was within the efficiency range of conventional furnace. The heat transfer coefficient of 4.48W/m^{2}K was obtained. Alumina bricks used in lining the furnace was attributable to its higher refractoriness. It was found that a better thermal shock was proved than clay bricks from the Comparative analysis simulation using commercial software ANSYS 14.0 aimed towards improving service life and efficiency.*

Keywords: *Aluminum, Secondary smelting, Refractory Bricks, crucible furnace, thermal efficiency, heat transfer coefficient*

1. Introduction

Aluminum is a renewable resource that has endless opportunities for generations to come (Osoba et al., 2018). Aluminum alloy manufactured components is well used in aerospace, automotive, packaging, offshore and marine constructions as it offers light weight, good corrosion resistance and excellent formability (Klauber et al., 2011; EAA, 2004). Aluminum and its alloy can be produced through primary and secondary smelting processes. Secondary aluminum often involve recycling aluminum scrap as the energy required for this process is ~5% of that required for primary aluminum production while yielding comparable quality aluminum as primary smelting (Das et al., 2007; Mukhopadhyay et al*.,* 2005). One of the means by which secondary smelting of aluminum could be performed is through the use of crucible furnace that may be open or close. In the early nineteenth century, the phenomenon of crucible furnace was applied to the experimental melting of non-ferrous metals. However, the previously used crucible furnaces in local foundries are associated with the many problems namely: full exposure to heat and combustible products which are harmful to the body and health, loss of heat due to the open nature of the local furnace, which leads to prolonged operational activities with undesired result.

Based on the method of generating heat, furnaces are broadly classified into two types, namely combustion type (using fuels) and electric type. Based on the kind of combustion, it can be broadly classified as oil fired, coal fired or gas fired (Mehta et al., 2013). The majority of the heat loss i.e. around 40% of heat input is flue gas loss and only an estimated 10% of available heat is lost through the refractory wall during steady state operating conditions (Whipple, 2008; Owolabi et al 2016). Furnaces vary in design, geometry, production capacity (melting rate), materials of construction, and mode of operation (Daviess, 1970). One of the major challenge in design optimisation of the aluminum recycling process is numerical modelling of the furnace (Khoei et al*.,* 1999; Khoei, 2000., Khoei et al 2002) in which this paper uses Ansys 14.0 to simulate the refractory bricks used for lining the furnace.

Ekpe et al. (2015) designed and fabricated an Aluminum Melting Furnace. Butane gas was used as the thermal energy source in heating up the system to the melting point of aluminum (660.4°C). Results showed great reduction in energy consumption and improved furnace efficiency of 28%. Many other researchers have worked on enhancing the performance evaluation of oil fired crucible furnace for melting al scrap, among others are Olukokun et al. (2019) with efficiency of 10.8%, Osarenmwinda (2015) with an improved furnace efficiency of 10.34%, Ighodalo et al. (2015) with a furnace efficiency of 11.5%, Adefemi et al. (2017) with an efficiency of 26.5%.

Furnace designs are made of different parts of different materials. The materials expand as temperature increases and contract as it decreases. This can lead to thermal fatigue causing cracking of the fuel fired crucible furnace linings. In practice, however, a lot of heat is lost in several ways, namely: energy conversion losses, furnace wall losses, furnace opening losses and the likes (Gilchrist, 1997; Holman, 1974; Trinks, 1967). The complexity of the phenomena that occur in real conditions makes it difficult to analyse accurately the study where conduction, convection and radiation occur concurrently on refractories used for furnace lining (Song et al., 1991).

Hence, the use of commercial software (Ansys, 14.0) can help get accurate result for the thermal analysis on the refractories used. Also the occurrence of high rate of fuel consumption and uncontrolled heat loss often limit the efficiency of crucible furnaces. Therefore, optimisation of these furnaces is of great importance to improve its performance (efficiency) during aluminum smelting for customised design of fuel fired crucible furnace. This current study presents the thermal characteristics evaluation results of an oil (diesel) fired furnace for the smelting of aluminum alloy. To minimise these losses, materials that can retain and conserve heat known as refractory materials can be used as lining materials in furnaces.

2. Methodology

2.1 Materials and Methodology

The following materials were specified for the design of the diesel fired crucible furnace: mild steel plate (3mm), 2 mm thick (ϕ 45) mild steel pipe gate valve, kaolin sand, refractory cement (durax) and flexible hose. Composition of the mild steel is shown in Table 1.

2.2 Method of Construction

The 10kg aluminum crucible furnace was designed majorly to melt aluminum and other nonferrous metals whose melting temperatures falls within its designed maximum operation temperature of 900°C. The major components of the 10 kg aluminum crucible furnace are: (i) furnace drum, (ii) furnace covers, (iii) air blower, (iv) fire bricks, (v) combustion chamber, and (vi) furnace cover opening/closing.

Hence, the design criteria are:

1. The furnace must be large enough to represent actual, working furnaces.
2. The furnace must be small enough that it would be useful as a research tool.
3. The furnace must be modular in nature.
4. The furnace must be able to be equipped with off-the-shelf facility and any custom equipment designed through the course of the project.

2.3 Major Features of the Furnace

The furnace component and material selection criteria are given in Table 2, and the bill of engineering measurement and evaluation as shown in Table 3.

Table 1. Compositional Analysis Result of Mild Steel Plate (MS)

C	Si	Mn	P	S	Cr	Mb	Ni	Al	Cu	Zn	Fe	V
0.2267	0.2361	0.0412	0.0412	0.0616	0.1343	0.0212	0.1014	0.0025	0.2588	0.0059	98.095	0.0027

Table 2. Material Selection Table

S/N	Furnace Component	Required Properties	Selected Material
1	Furnace unit	Ability to withstand internal pressure of 276 MPa – 2070 MPa	3 mm thick mild steel
2	Crucible pot	High heat resistance, high strength and good thermal conductivity	Graphite and silicon carbide
3	Cover	Ability to withstand internal pressure of 276 MPa – 2070 MPa	3 mm thick mild steel
4	Blower	Light weight and ease of shaping	Aluminum 220V, 1.6A, 50/60Hz
5	Air pipe	Resistant to corrosion and heat	Mild steel
6	Furnace insulator/ lining	Good resistant to heat flow per unit thickness, with high thermal conductivity	Refractory mixture of Durax, and water
7	Fuel tank		2 mm thick mild steel bucket

Table 3. Bill of Engineering Measurement and Evaluation

S/N	Material description	Unit	Quantity	Unit cost ₦	Total cost ₦	Dollar Equivalent ($)
1	5 x 65 x 65 angle bar	2.4 cm	2	2,300	4,600	12.70
2	Furnace drum		1	12,000	12,000	33.20
3	Fuel tank		1	2,000	2,000	5.53
4	Tap or valve		1	500	500	1.38
5	Rubber tubing		1	3,000	3,000	8.29
6	Clips		10	200	2,000	5.52
7	Meter rule	mm	4	100	400	1.10
8	230 x 115 x 65 brick		30	1,000	30,000	83.00
9	Diesel fuel	litre	2	200	400	1.00
10	Bolt and nut		10	100	1,000	2.80
11	Blower		1	35,000	35,000	97.00
12	Galvanized pipe	800 mm Length	1	4,600	4,600	13.00
13	Kaoline clay	kg	1	3,000	3,000	8.30

Table 3. *(Continued)*

S/N	Material Descriptions	Unit	Quantity	Unit cost ₦	Total cost ₦	Dollar Equivalent ($)*
14	Water	20 litre gallon	3	10	30	0.08
15	Cutting Disc	4.5 inches	3	1,500	4,500	12.50
16	Guage12 electrode	Packet	2	1,800	3,600	10.00
17	Crucible pot		1	35,000	35,000	97.00
18	Plank	Length	1	1,600	1,600	4.40
19	Calcium aluminate cement (Durax 1600)		2	15,000	30,000	83.00
20	Pyrometer		1	35,000	35,000	97.00
21	Transportation/Miscellaneous			15,000	15000	41.50
22	Total overall cost				₦223,230	616.00

* - Remarks: Exchange rate ₦/$=362

2.4 Modelling of Refractory Bricks

Three dimensional model of a refractory brick is represented in Figure 1. The bricks were modelled using Solid Works software. Thereafter, the model was imported into ANYS workbench 14.0 for analysis. Thermal properties were built in the engineering data software for the varied bricks (see Table 4). The set up for the analysis was done with a finite element mesh on the model. While in the Model, the configured thermal properties were assigned to the geometry, and varied properties were examined at a temperature of 750ºC. The set mesh of the refractory bricks has statistics of nodes and elements 28,807 and 6,300, respectively (see Figure 2).

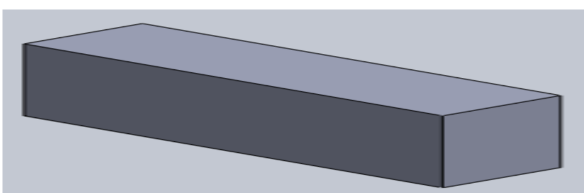


Figure 1. 3-D Model of the Crucible Brick

Table 4. Thermal Properties of Clay Bricks and Alumina Refractory

Material properties	Clay Bricks	Alumina
Density	$2100 kg/m^3$	$3980\ kg/m^3$
Melting	1230ºC	2100ºC
Maximum service temperature	927ºC	1300ºC
Thermal conductivity	0.73W/mºC	38.5W/mº C
Specific heat capacity	850J/kgºC	820J/kgº C
Thermal expansion coefficient	$8*10^{-6}$ Strain/ºC	$7.9*10^{-6}$ Strain/ºC

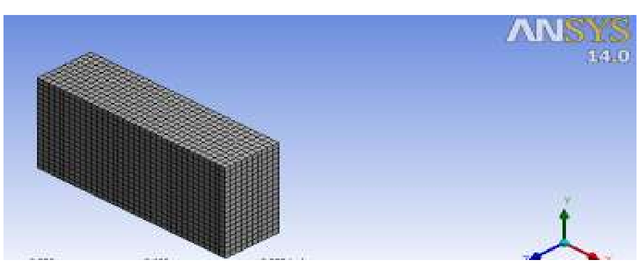


Figure 2. Finite Element Mesh of the Bricks

3. Results and Discussion

3.1 Comparative Analysis of Refractory Bricks

From the transient thermal analysis result, it was observed that the maximum heat flux of clay bricks (see Figure 5) and Alumina bricks (see Figure 3) is 4.750*105 W/m^2 and $5.2394*10^6$ W/m^2, respectively, and the maximum directional heat flux of clay bricks (see Figure 6), and alumina (see Figure 4) were found to be $3.7723*10^5 W/m^2$ $5.2394*10^6$ W/m^2, respectively. Comparatively, it was observed that, thermal loading was high in clay bricks.

This is as a result of higher specific heat capacity and thermal expansion coefficient of alumina refractory (Xin, 2013; Lee, 2000). Thus, the refractory lining of the furnace under transient conditions should have excellent thermal shock properties i.e., volume stable, high thermal conductivity, and low thermal expansion (Nandy and Jogai, 2012). Hence, alumina will exhibit low thermal load and thermal shock which will enhance the durability and suitable for the lining of the wall of the crucible furnace for non-ferrous metal application.

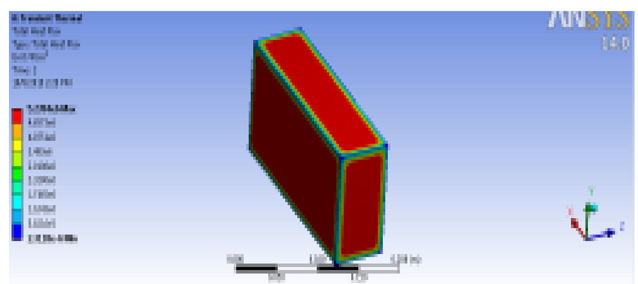
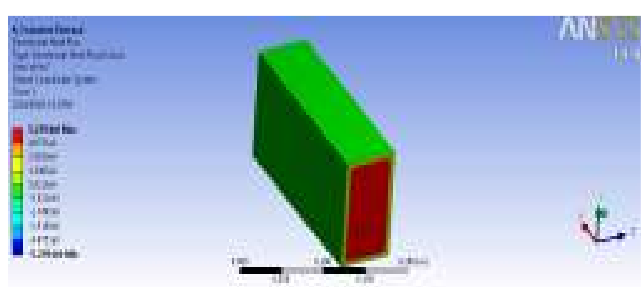


Figure 3. Total Heat Flux of Alumina Brick



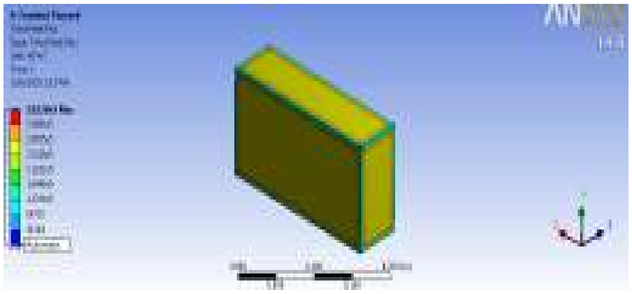


Figure 5. Total Heat Flux of Clay Bricks

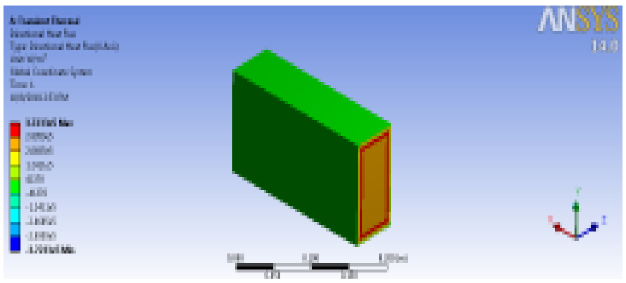


Figure 6. Directional Heat Flux of Clay Bricks

3.2 Design Analysis

The aluminum melting furnace was evaluated to ascertain its performance by melting aluminum scraps at a temperature of 660 °C (933K). Preheating was done in the first 10 minutes to enhance good heat distribution in the combustion chamber. The results obtained were tabulated as indicated in Table 5. The efficiency of the furnace was calculated to be 29.70%, which falls within the efficiency range of conventional furnace, showing that most of the heat generated in the furnace was used in the melting of the metal.

Solid works 2014 was used for the 3D model and Wire frame model as seen in Figures 7 and 8, to show the skeletal view of the customised crucible furnace. The furnace drum was made from a 3 mm thick mild steel plate rolled into a cylinder of diameter of 510 mm and height 470 mm with the overall combustion space of diameter 495 mm and height 320mm.

Detailed dimensions of the furnace drum are as follows:

a) Height of the furnace drum before laying bricks (h) = 470 mm
b) Height of combustible space of the furnace drum after laying of bricks (h_1) = 405 mm
c) Internal diameter of the furnace drum before laying of bricks (d) =510 mm
d) Internal diameter of the furnace drum after laying of bricks (d_1) = 495 mm
e) Inlet diameter of the burner nozzle = 30mm
f) Outlet diameter of the burner nozzle = 40mm
g) Height of the cover = 120 mm
h) Total height of the drum = Height of drum + height of cover = 470 + 120 = 590 mm.
i) Diameter of the chimney hole (on cover) = 100 mm
j) Thickness of the metal plate = 3 mm
k) Total height of the crucible furnace = 470+120 = 590 mm
l) Height of the crucible body = 170 mm
m) Thickness of the crucible = 10 mm
n) Diameter of the crucible = 150 mm
o) Thickness of the Durax lining = 50 mm
p) Height of furnace cover = 120 mm
q) Diameter of furnace cover = 510 mm

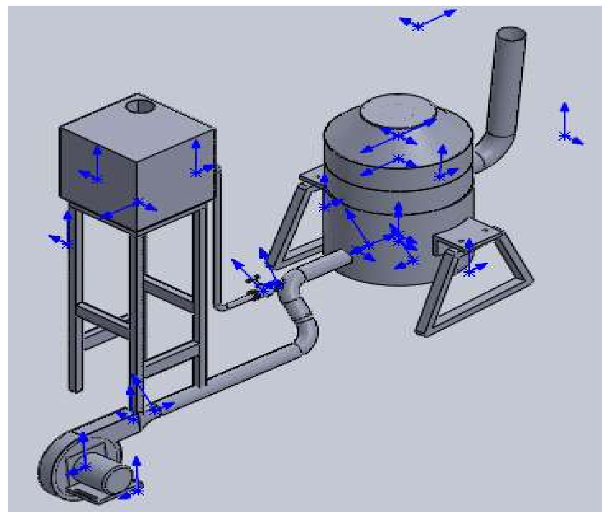


Figure 7. 3-D Model of the Furnace

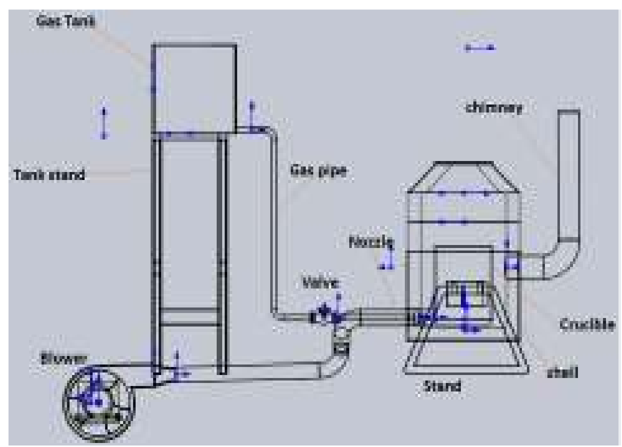


Figure 8. Wire Frame of the Furnace Assembly

Volume of combustion chamber (Combustible Volume of furnace after laying of bricks):

$$V_1 = \frac{\pi D_1^2 H_1}{4} \quad (1)$$

$V_1 = (3.142 \times 405 \times 495^2) / 4$
$= 311796762.75 mm^3$
$= 0.3118 m^3$

Table 5. Transient Time-temperature Result during Pre-heating and Actual Melting

Time (min)	Temperature(°C)	Heating Rate (°C/min)
0	25	
5	150	30
10	400	40
0	400	
10	500	50
15	740	49.33
20	980	49.0
Average		49.44

3.3 Efficiency of the Oil-fired Crucible Furnace

Heat energy Q_1, needed to raise the temperature of the metal from room temperature to the melting point of the metal, determined as: $Q_1 = Mc_{p1}(T_m - T_A)$ (Sinha and Goel 1973). According to Suresh and Nagarium (2016), specific heat capacity of aluminum (solid) is 0.91KJ/Kg.K. Hence, based on Kothandaraman and Subramanyan (2014), specific heat capacity of aluminum (molten) is 1.18KJ/Kg.K. Given other parameters below:

Latent Heat of Fusion of Aluminum = 321KJ/Kg
Melting Point of Aluminum = 660°C
Ambient temperature T_A =25°C
Mass of Aluminum melted = 5kg

$$Q_1 = Mc_{p1}(T_m - T_A) \tag{2}$$
$$= 5 \times 0.91 \times 10^3 (933 - 298)$$
$$= 2889.25KJ$$

Energy Q_2 needed to raise the temperature of the metal from room temperature to the melting point of the metal (Sinha and Goel, 1973).

$$Q_2 = mL \tag{3}$$
$$= 5 \times 321 = 1605\text{KJ}$$

Energy Q_3 (super heat) required to raise the temperature of molten metal from its melting point to the required pouring temperature (750°C) (Sinha and Goel, 1973).
It is given as:

$$Q_3 = Mc_{p2}(T_p - T_m) \tag{4}$$
$$= 5 \times 1.18 \times (1023 - 933)$$
$$= 531\ KJ$$

Heat required for a melt, Hear output, Q_n

$$Q_n = Q_1 + Q_2 + Q_3$$
$$= Mc_{p1}(T_m - T_A) + mL + Mc_{p2}(T_p - T_m) \tag{5}$$

Total energy required by aluminum

$$Q_n = 288925 + 1605 + 531 = 5025.25\ KJ$$

The total amount of energy consumed in the furnace is calculated by multiplying the number of litres of fuel by the energy content per litres of fuel used. Energy content of fuel is rated 139000 KJ/gallon (1 gallon = 4.6 litres). Therefore, energy content of the fuel is

$$139000/4.6 = 30217.39KJ$$

0.58 liters of fuel was used to melt the 5Kg mass of aluminum. Therefore, total amount of energy used by the furnace = 0.56 x 30,217. 39 = 16921.74*KJ*

Theoretical thermal efficiency of the furnace is given by

$$\eta = \frac{\text{Heat output of the furnace}}{\text{Heat supplied by the fuel}} \times 100\% \tag{6}$$
$$= 5025.25 / 16921.74 \times 100\%$$
$$= 29.70\%$$

From Newton's law of cooling equation;

$$Q/A = hc\ \Delta T \tag{7}$$

where,
Q = heat flow rate
A = area of cylinder
h_c= heat transfer coefficient
ΔT = temperature difference across wall

The heat output is calculated as follows

$$Q = Mc_{p1}(T_p - T_A)$$
$$= 5 \times 0.91 \times 10^3 (1023 - 298) = 4540.9KJ$$

$$\text{Area of cylinder} = 2\pi r\,(H + r) \tag{8}$$
$$= 2 \times 3.142 \times 247.5\ (405 + 247.5)$$
$$= 1555.29(652.5) = 1014826.725mm^2 = 1.015m^2$$

$$\Delta T = 1023 - 298 = 998K$$

Substituting

$$h_c = Q / A\ \Delta T$$
$$= 4540.9 / (1.015 \times 998) = 4.48W/m^2K$$

The results in Table 5 show that the melting furnace can achieve its main objective of recycling laboratory sie aluminum (5 Kg) in a single operation. A significant improvement in efficiency (29.70%) was recorded compare to 4-6 % in using the traditional furnace (Ilori, 1991) and 28% efficiency from Ekpe et al. (2015) due to the use of better refractories (Alumina bricks and refractory cement) It also takes a shorter time to melt the aluminum because of the improved heating rate of furnace at 49.44°C/min, which will aid great reduction in the energy consumption .Calculated heat transfer coefficient is higher compare to that obtained by Ekpe et al. (2015).

The developed furnace will not only melt Aluminum but also any metal that has melting temperature below 1500°C. When compared with the efficiency of 25% obtainable from the conventional crucible furnace (Bureau of energy efficiency, 2019).

4. Conclusion

The designed and developed oil-fired crucible furnace was used to melt aluminum scraps and the following inference are made:

1. The crucible furnace proved to be effective for melting of aluminum and other aluminum alloy
2. Selection of appropriate refractories during fabrication enhances the efficiency and productivity of furnaces
3. The locally designed and developed furnace is comparatively economical and time saving during operation compared to investigated furnace in literatures

4. The device is suitable for use in small scale foundries and tertiary institutions, and
5. The locally designed and developed furnace is recommended for use in small scale foundries and tertiary institutions laboratory and workshop.

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