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Review

Natural rubber (*Hevea brasiliensis* Müell.-Arg.) production, processing, and rubber wastes utilization: Challenges and prospects for economic diversification and sustainable development of Nigeria

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Over 80% of Nigeria's foreign exchange earnings come from the sales of crude petroleum. Nigeria has a landmass of 910,768 km^2 with 38.97% arable, while 3.46% is suitable for the cultivation of permanent cash crops such as rubber, cocoa and palm trees. High-latex yields (3,000-3,500 kg dry natural rubber (NR)/ha/year) of Nigeria's hybrid rubber seedlings is a preferred choice to most foreign species (900-1,600 kg dry NR/ha/year) for cultivation in sub-Saharan Africa. In 2018, Nigeria's rubber export of US$41.8 million for global sales of US$13.1 billion was considered low compared to other African leading producers (Côte d'Ivoire-US$752.6 million, and Liberia-US$126.2 million). The present government's efforts to increase rubber cultivation at an annual growth rate of 5.7%, could be instrumental to diversifying its revenue base as demand for rubber-derived products is on a global increase. The challenges faced by small-scale rubber farmers are being addressed by government through the provision of affordable credit facilities and improved genetic seedlings for planting. Potential markets exist for micronized rubber powders sourced from waste tyres for the production of value-added fine chemicals, road construction, athletic and recreational facilities etc. Also, slurries and biogas obtained from natural rubber processing plants can also act as catalysts for sustainable development of the economy.

Key words: Nigeria, Agriculture sector, cash crops, rubber farming, rubber export, gross domestic product.

INTRODUCTION

This review paper discusses the impact of agriculture sector on the Nigerian economy in the 1960s, and the neglect of the sector as a result of the oil boom of 1970s. The natural rubber (NR) industry was a major contributor to the growth of Nigeria's gross domestic product (GDP) with robust foreign reserves in the pre-oil boom era.

The challenges and prospects of rubber farmers in Nigeria, assessment of natural rubber production and processing in pre- and post-civil war era in Nigeria, and conversion of rubber wastes to wealth for increased revenue generation are reviewed and discussed.

Nigeria has total landmass coverage of 910,768 km^2 with about 38.97% arable, while 3.46% is available for the cultivation of permanent cash crops (Chevron Nigeria Limited, 2015; Odetola and Etumnu, 2013) such as rubber, cocoa and palm trees. From 1960 until the oil boom of the 1970s, the main source of revenue in Nigeria was agriculture with surplus food produced for her entire population, such that over 70% of the total export came from natural rubber, cocoa, palm oil, and groundnuts (Oluwaseyi, 2017; Abolagha et al., 2016). About 60% of Nigerians were directly or indirectly employed in the agriculture sector. The sector also produces millet, tomatoes, gum arabic, sesame seeds, cotton, cashew nuts, citrus fruits, maize, cassava, yam, and sugarcane on a smaller scale. Infrastructural developments then, were quite visible with the prospects of a bigger bio-based economy in future. In the 1970s, the agriculture sector was neglected because of the oil boom and efforts by previous governments to revive this sector that produces natural rubber, cocoa, palm oil, and groundnuts, seen as the biggest foreign exchange earners for Nigeria failed as oil money was handy (Oluwaseyi, 2017). The agriculture sector at that time contributed about 64% to the total GDP, but this gradually declined to 8% in the 1970s, and 19% in 1985 (Izuchukwu, 2011). In addition, a report by the World Bank indicated a declined percentage of employment (public and private) in the agriculture sector as against the total employment in Nigeria between 1991 and 2019 at an average of 44.01% with a minimum of 36.38% in 2019 and maximum of 50.17% in 1992 (World Bank, 2019) compared to 60% prior to oil boom era. Revenue generation from the sales of about 2.1 million barrels of crude oil/day from the estimated oil reserves of 37.2 billion barrels, and sales of gas from the reserves of 187 trillion standard cubic feet of natural gas deposits did not adequately impact positively on the GDP's growth in the later years (Ishola et al., 2013; Ohimain, 2013; Omo-Ikerodah et al., 2009). Recently, the government introduced the Economic Recovery and Growth Plan (ERGP: 2017-2020) as a road map to diversify the economy, which depended on the sales of crude oil with emphasis on agriculture to create jobs, reduce food imports and support the growth of her GDP (Ejeh and Orokpo, 2019). *Hevea brasiliensis* Müell.-Arg tree (Figure 1) (Willd. ex Adr. de Juss.) is purposely cultivated for the production of latex as a source of NR for the production of over 50,000 products (Takase et al., 2015; Ng et al., 2013; Atabani et al., 2013). NR latex $[(C_5H_8)_n]$ is a polymeric material of *cis*-1,4 polyisoprene (2-methyl-1, 3-butadiene) with a molecular weight in the range ≥300,000. It contains 30-35% rubber, 2-3% proteins and lipids, 0.3% resins, 1.5-4% glycosides, and the remainder is water (>50%) (Kumar and Nijasure, 1997). Due to the global shortage of NR for rubber-related products, the current rubber market is dominated by synthetic rubbers (SRs) sourced from fossil petroleum and vulcanized with sulphur atoms to produce chain of artificial polymers (e.g., styrene/1, 3-butadiene, and isobutylene/isoprene). For instance, styrene-butadiene rubber (SBR), isobutylene-isoprene rubber (that is, butyl rubber, abbr. BR), and *cis*-polybutadiene rubber (CBR) are the three most common SRs used in tyre production (Kan et al., 2017). A tyre may contain synthetic rubber, natural rubber, carbon black, steel wires, fabric, plasticizers, lubricants, antioxidants, and inorganic materials (e.g., calcium carbonate and silica). Synthetic rubbers from petrochemicals could be in short supply when the uses of fossil materials are reduced in the nearest possible future arising from the global Paris Agreement on climate change (UNFCCC, 2015). It is therefore envisaged that NR may be seen as the 'oil' of the future especially with the current expansion of the automobile industry and the global drive to using rubber-modified products, industrially.

The Nigerian government introduced a 12-year (2006-2018) Rubber Initiative Plan for increased rubber production for local use and export through aggressive cultivation of new plantations and rehabilitation of old plantations to achieve a target of 360,000 ha (Umar et al., 2010), which outstandingly yielded 371,775 ha of harvested rubber plantations (FAO, 2017). Thus, with the government's current expansion of rubber plantations, export earnings are projected to increase significantly by end of the current decade considering the renewed drive by the government to diversify the economy through the agriculture sector. NR production by small-scale rubber farmers was generally as low as 500 kg dry NR/ha/year in recent years, which was attributed to over-aged rubber trees (≥ 30 years), poor maintenance culture, lack of credit facilities, and non-availability of certified rubber seedlings for planting as reported by a cross section of small-scale rubber farmers (Field surveys). The primary objective of the initiative is to increase the income of the rubber farmers through increased local production and

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utilization of NR, creation of employment, and export the excess to boost the economy. This is perceived to ultimately diversify the economy and enhance the income of small-scale rubber famers who account for about 85% of hectares of rubber plantations (Umar et al., 2011). Recent survey shows that Nigeria produced 159,264 tons NR in 2017, second in Africa after **C**ôte d'Ivoire (580,000 tons), and ranked 13th in global production (FAO, 2017). Nigeria's annual export of 127,000 metric tons NR brought in export earnings of US$37 million in 2017 (NEPC, 2018). Global sales from NR exports by producing countries in 2018 totalled US$13.1 billion, and this reflected an average decline of 22.1% since 2014, when the world's shipment of NR was US$16.8 billion (Workman, 2019). In 2018, Nigeria's rubber export was US$41.8 million (0.3% global sales), while **C**ôte d'Ivoire (5.7% global sales-US$752.6 million) and Liberia (1% global sales-US$126.2 million) were the biggest exporters from Africa (Workman, 2019). Industrial applications of rubber tree products, apart from the products from NR and biofuels production, are numerous. With encouragement from government at all levels, through the provision of credit facilities for plantation owners, Nigeria may closely approach the production levels of Southeast Asian countries that account for over 90% of global NR production (Umar et al., 2011). Globally, the production of NR was reported at a 5.2% growth rate, Africa at 2.2%, while Nigeria's growth rate estimated at 5.7% (Umar et al., 2011). Onoji et al. (2016) reported that 18 million ha of land is available in South-South geopolitical region of Nigeria with good climatic factors (20-35°C, and 1800-4000 mm annual rainfall) required for the growth of rubber trees and good yields of NR. Unsuccessful trial cultivations were carried out in some Northern States of Nigeria where annual rainfall rarely exceeds 650 mm in the months of June to August considered as peak periods of rainy season (Umar et al., 2010). Rubber tree has a growth period of 6 to 9 years before commercial production of latex, but the seeds spring out between 4 and 6 years of growth (Eka et al., 2010). At present, non-edible rubber seed oil has the potential to generate about 8,000 tons/annum biodiesel in Nigeria using waste rubber seed shell as bio-catalyst (Onoji et al., 2017). The collection of rubber seeds for biodiesel production can be an additional source of income to rubber farmers who also practice intercropping with arable crops such as cassava, pineapple, yam, pepper, bitter leaf, maize, groundnut, and rice for sustenance, soil improvement and weed control mechanisms before NR production commences (Esekhade et al., 2019). The Rubber Research Institute of Nigeria (RRIN) genetically developed Nigerian rubber seedlings code named NIG800 and NIG900 series with yields 3,000 to 3,500 kg dry NR/ha/year when compared with imported seedlings from Southeast Asia countries, whose yields range from 900 to 1,600 kg dry NR/ha/year (Umar et al., 2010). The Nigerian seedlings are presently made available to small-scale rubber farmers and estate rubber planters for cultivation to address the challenges of low NR production. It is expected that in the next two decades, Nigeria will play a leading role in global NR production in a diversified sustainable agricultural-based economy. Due to expansion of the transportation sector in Nigeria, expired and used tyres are commonly dumped in unregulated dumpsites. This constituted an environmental hazard and exacerbated health problems to humans when these wastes are not properly disposed of. Pyrolysis is a thermochemical process that can be scaled-up to process the waste tyres in Nigeria into useable products, and recover the energy for domestic and industrial applications.

METHODOLOGY

Google scholar, a fast internet-based search engine was used to obtain information from online databases which include: Directory of Open Access Journals, Web of Science, African Journals Online, ScienceDirect, Research4Life, ResearchGate, etc.

Furthermore, publications from peer reviewed journals, conference papers, proceedings of national and international workshops, RRIN's manuals, government and biennial reports, FAO and corporate organizations' publications, book chapters and postgraduate theses published from year 1997 to 2020; and field interviews with rubber farmers were considered for this review. The materials were screened and relevant data extracted, analysed/or studied, and recorded for the review write up.

FINDINGS AND DISCUSSION

Challenges and prospects of rubber farms in Nigeria

Nigeria presently stands as the second largest producer of natural rubber in Africa with only 50% of the rubber plantations exploited (Ogbebor, 2013). Small-scale rubber farmers opted for food crops production and felling of aged-rubber trees for firewood as a source of energy for sustenance. The long gestation period of rubber tree, without income before maturity for latex production was perceived as non-beneficial to the plantation owners (Esekhade et al., 2019). Major stakeholders in the rubber industry believed that the Presidential Initiative on rubber cultivation needed to be reinvigorated for greater impact. Government at all levels, is expected to assist in the development of seed gardens/nurseries to produce quality budded materials for distribution to local rubber farmers at subsidized rates. This will prevent the use of uncertified seedlings for planting that result in low yield of NR and rubber seeds.

The rubber industry in Nigeria provided employment opportunities for the locals, and served as a major source of revenue in the 1960s (Otene et al., 2011). The mandate of RRIN is to carry out research into genetic

Figure 1. Typical latex collection from tapped rubber tree.

improvement and development of high yield rubber hybrids to assist the small-scale, and large-scale farmers such as RRIN Estates, Michelin Rubber Estate, Pamol Rubber Estate Calabar, Rubber Estates Nigeria Limited Udo, and Rubber Plantation Estate Urhonigbe (Umar et al., 2010; Otene et al., 2011). RRIN is also required to provide technical supports and information through improved technologies and diversified farming systems to enhance and improve the activities of the rubber farmers. Genetically developed Nigerian rubber hybrids (NIG800 and NIG900 series) used for inter-location trials at Akwete (Abia State), Calabar (Cross-River State), and Okho in Edo State in Nigeria have outstanding results in terms of natural rubber yields (Umar et al., 2010). It is expected that these high yield Nigerian rubber hybrids, which are resistant to wind and disease (Onoji et al., 2020), should dominate rubber plantations in Nigeria for bigger export in future. Available reports showed that in the past years, budded rubber stumps for these hybrid rubber seedlings are in limited supply at RRIN; and thus they are not available in required quantity for the small-scale rubber farmers that owned a majority of cultivated and tapped rubber plantations in Nigeria (Umar et al., 2010). The foregoing necessitated their engagement in the practice of small-size farming of other cash crops to complement income from rubber farms (Esekhade et al., 2019; Umar et al., 2011). RRIN's operations also include amongst others, collaboration with the Nigerian Export Promotion Council (NEPC), and their foreign partners such as the International Rubber Study Group (IRSG), Common Fund for Commodities (CFC) and World Agroforestry Centre (also known as ICRAF-International Council for Research in Agroforestry) to promote development of economically viable small-scale rubber businesses in Nigeria. NEPC is already intervening by providing farmers with 5,000 improved rubber budded seedlings and coordinating synergetic cooperation among rubber producers, processors, and exporters in Nigeria.

Other challenges facing the small-scale rubber farmers in Nigeria as reported by Abolagha and Giroh (2006) include:

(1) Low levels of mechanization for yield improvement;
(2) Aging rubber trees;
(3) Lack of commodity Boards to support investors;
(4) Poor investments in rubber farming;
(5) Inadequate supply of raw materials (latex and cup lumps) to the processing plants;
(6) Withdrawal of subsidies from pesticides, chemicals and farming implements;
(7) Inadequate provision of credit facilities to the smallholders of rubber farms;
(8) High production cost of NR;
(9) Diversion of loans by farmers to other areas of needs;
(10) Inadequate database for policy formulation and program planning;
(11) Rural-urban migration culminating in scarcity of

Table 1. Technical specifications of NSR**.**

Constituent	NSR10	NSR20
Dirts wt.%	≤0.1	≤0.2
Ash wt.%	≤0.75	≤1
Nitrogen wt.%	≤0.6	≤0.6
Volatile matter wt.%	≤0.8	≤0.8
Initial plasticity (P_o), min	≥30	≥30
Plasticity retention index (PRI, min) ISO 2930:2017	≥50	≥40

NSR: Nigerian standard rubber; min: minutes.
Source: Ogbebor (2013).

labour;
(12) Weak agricultural extension delivery services with poor feedback mechanism;
(13) Inconsistency and instability in macro-economic policies which do not engender confidence in the economy and tend to discourage medium- and long-term investments;
(14) Lack of involvement of stakeholders in program design;
(15) Poor monitoring, evaluation and implementation of farming programs.

Climatic factors are critical to NR production in Southern Nigeria, with the highest production attained in the months of December-February when a hazy harmattan wind persists. The rainy season peaks between the months of June and July, with drought in the latter part of August within the rubber producing states in Southern Nigeria. Rains hinder tapping during these periods, and this result in low outputs (field interviews with farmers). Labour is oftentimes mobilized to other sections such as field maintenance, cleaning of rubber cups, preparation of tapping utensils, and intercropping activities within the perimeter of the rubber plantation. Multiple intercropping with revenue from pineapple, cassava, pepper, okra, cocoyam, and maize crops in the vast interior of young rubber plantations holds the key to attracting small-scale rubber farming (Otene et al., 2011). In Nigeria, a majority of the rubber tappers are younger, matured workers within the age bracket of 30 and 40 years, and over 70% of them are male with little or no formal education. An experienced rubber tapper in Nigeria can tap about 450 to 600 trees/day on the average of 30s/tree for a standard half-spiral system.

Assessment of NR production in Africa-Nigeria in focus

Natural rubber played a dominant role in the economic development of Nigeria in the 1960s placing third to cocoa and palm oil as major foreign exchange earners (Umar et al., 2011).

Nigeria was the biggest producer of NR from 1961 (58,000 tons) to 1966 (73,500 tons) with Liberia being the runner-up (FAO, 2017). NR in different forms is processed into products that meet Nigerian standards (Table 1). These products such as concentrated latex, baled crumb rubber, ribbed smoked sheet (Figures 2 and 3), and crepe rubber are consumed locally and the excess are exported to boost foreign reserves. With the outbreak of the Nigerian civil war in 1967, production from Nigeria declined to 52,000 tons compared to Liberia's 62,290 tons in 1967 (FAO, 2017). Liberia continued to be the leading producer of NR in Africa, even after the post-war era in Nigeria. Liberia's production declined to 40 tons in 1990 as a result of the outbreak of the Liberian civil war in 1989. While the civil war in Liberia lasted, Nigeria regained the leading role as an Africa producer of NR till 1998. With the decline of NR production in Nigeria from late 1990s to 2002 due to aged trees (≥ 30 years), lack of trained labour and incentives from government, Côte d'Ivoire became Africa's biggest producer with a production of 580,000 tons compared with Nigeria's 159,264 tons in 2017 (FAO, 2017). During the peak production periods, the rubber industry in Nigeria had 54 factories with an overall installed processing capacity of 600,000 tons NR/year, but operated at 20% capacity. This gradually reduced to about 20 factories due to government neglect of the sector which resulted in a loss of about 40% in rubber exports (Gaille, 2018). A cross-section of small-scale rubber farmers interviewed at RRIN recommended that the government should subsidize 80% of the cost associated with plant budded seedlings for the farmers. This will cover long-term expenses that are necessary to bring rubber trees to maturity in order to earn more income from sales. The international price of NR steadily increased to about US$1,930/ton between the months of January and June 2017 (Thomas et al., 2019). There are expectations from stakeholders and industrialists that the changes will become a huge source of revenue to producers in the near future. On a global scale, and to meet increased demand for rubber, increase in hectares

Figure 2. Rubber sheets hung on reapers in a smokehouse.
Source: Aigbodion (2017).

Figure 3. Ribbed smoked sheet awaiting bailing process for export.
Source: Aigbodion (2017).

Table 2. Compositional analysis of biogas from NR processing plant.

Component	%
Methane	65
Carbon dioxide	30
Hydrogen sulphide	2.5
Ammonia and water vapour	2.5

Source: Aigbodion (2017).

under new cultivation by small-scale and large-scale rubber farmers should be intensified in Nigeria and other rubber producing nations. To achieve this, for instance, cooperative societies in Delta State, Nigeria, acquired over 75,000 ha of land for cultivation of new rubber plantations. This will engage large number of unemployed youths; which may accelerate the transformation of Nigeria into a leading producer of NR in the global market. In the same vein, the International Tripartite Rubber Council (ITRC) with memberships drawn from the major NR producers in Southeast Asia (that is, Thailand, Indonesia, and Malaysia) accounted for about 63% of World's NR production in 2017. Members of the Council implemented their collective "Agreed Export Tonnage Scheme (AETS)" for an export reduction of about 700,000 tons in 2019 as a response to a request from other producers for an increased market price of NR (Thomas et al., 2019). This intervention will further stabilise the international price of NR and enables it to compete favourably with other cash crops in revenue generation for rubber producing countries. However, the ITRC member nations are constrained with land challenges for NR cultivation due to severe competition for land by other cash crops such as palm trees. With the vast arable land in West and Central Africa sub-regions, Nigeria is a targeted choice destination for foreign investments in rubber plantations. The natural rubber industry in Nigeria has a potential for sustainable growth and development considering the government's policy on diversification of the economy through the sustainability of the private sector-driven agricultural sector.

Renewable energy from natural rubber factories

The NR processing factories in most rubber producing West Africa countries are perceived as filthy places of work because health, safety and environment laws are not often fully complied with. The effluents (serum wastewater, etc.) from such factories are not adequately disposed of; hence they constitute a menace to the environment. However, if properly digested, the effluents could be sources of renewable energy like biogas (methane) for heat and power generation purposes. A compositional analysis of effluents from a typical NR processing plant in Nigeria (Table 2), has been reported by Aigbodion (2017). The heating value of the biogas falls within the range of 18.6 to 26.1 MJ/m^3, and therefore suitable for domestic applications such as heat generation, while the slurry obtained after the digestion process has potential application to be converted to bio-fertilizer similar to rubber seed oil cake. A typical rubber factory processing 2.1 metric ton NR/day could generate 40 m^3/day of biogas, thus providing a minimum 744 MJ/day of energy (Aigbodion, 2017). Production of biogas from NR processing plants would most certainly be an additional source of revenue to Nigeria as reported in countries such as Sri Lanka, Malaysia, and India that are currently using biogas obtained from rubber factories (Aigbodion, 2017).

Industrial uses of rubber wood

The economic life span of rubber trees ranges from 25 to 30 years; thereafter, the trees are felled and replanted to maintain high latex production (Coulen et al., 2017). However, there is a growing interest in technical applications of rubber wood for furniture factories, energy generation (as firewood and charcoal), and in pulp and paper industry. In the Asian continent, studies have shown that rubber wood is significantly being utilized for various purposes in Thailand, Malaysia, Cambodia, and India. Rubber wood is considered a source of cellulose nanofibers which possess a vast range of potential applications in areas such as biomedical, electronics, packaging, nanocomposite, gas barrier films, and optically transparent functional materials (Aigbodion, 2017). There are limited technical applications of rubber wood in African countries especially the major rubber producers such as **C**ôte d'Ivoire, Nigeria, Liberia and Cameroon. In these countries, the wood is often burnt off or used as firewood and charcoal for heat generation by the locals, but this could generate substantial revenue if properly harnessed. Table 3 depicts the typical properties of rubber wood in comparison with other common tree woods in Nigeria.

Table 3. Comparison of properties of rubber wood with other tropical rainforest woods in Nigeria (at 12% moisture content).

Species	Density (kg/m^3)	Static bending		Volume Shrinkage (%)
		MOR (N/mm^2)	MOE (N/mm^2)	
Rubber wood (*Hevea brasiliensis*)	570	66	9,240	11.5
Apa (*Afzelia africana*)	823	136	6,313	7.6
Ita (*Celtis mildbraedii*)	732	149	7,088	12.2
Iroko (*Meliceae excelsa*)	650	90	5,765	9.1
Mahogany (*Khaya ivorensis*)	525	94	8,192	12.9
Obeche (*Triplochiton scleroxylon*)	372	30	3,937	6.9

MOR: Modulus of rupture; MOE: Modulus of elasticity
Source: Aigbodion (2017).

Rubber wastes to wealth?

Global population explosion, industrialization, urban development, and change in consumption patterns are responsible for the present huge global waste generation. A differential part of this waste comes from the auto industry as waste tyres (Li et al., 2016). Disposal of waste, used tyres in particular, is a major concern to waste management authorities in Nigeria because it is seen as a service to be rendered by the government. However, from the perspective of sustainable development and need for a cleaner environment, it is a collective responsibility of every individual in the society (Oh and Hettiarachchi, 2020).

In Nigeria, waste tyres are stockpiled at homes, auto-service centres, roadsides, and often disposed of in unregulated landfills and dumpsites that pave way for the proliferation of disease vectors such as the *Aedes aegypti* mosquito, Zika (Zanchet and de Sousa, 2020), and breeding sites for rodents (Umeki et al., 2016). In most cases, waste tyres are burnt during protests (e.g., #EndSARS; that is, Police brutality against youths in Nigeria), riots, and other civil disturbances, creating hazardous gases and dirt which result in serious health problems and environmental challenges. In extreme cases, they are used as roasting materials in abattoirs, which could cause serious health problems from consumption of the meat (Harrison-Obi, 2019).

The shortcomings of the conventional approach to managing disposal of waste tyres can be addressed through the use of more friendly green technologies to recover material and generate energy for domestic and industrial applications. With the fast depletion of natural resources, and to meet stringent emissions standards, reduction in waste tyres by reincorporating them into production processes will add value to what was hitherto considered valueless (Ramirez-Canon et al., 2018).

Waste valorization via thermochemical process is a promising method used to create wealth from waste tyres because of its simplicity, cost-effectiveness, and high purity of products. Pyrolysis is a valorization process that can be used to recover energy and value-added products from waste tyres due to challenges involved in tyre recycling and reuse (Kan et al., 2017; Smelik et al., 2015). The pyrolysis process conditions can be optimized to favour products of interest such as bio-char, oil (C_5-C_{24}), and gases (C_1-C_4) (Osayi et al., 2018). Studies have shown that pyrolysis at different temperatures can be used to monitor the compositions of the value-added products and by-products. Due to the rate of evaporation of chemical compounds used in tyre formulation, the yield of pyrolytic fractions from waste tyres can be varied with temperature (Ramirez-Canon et al., 2018; Osayi et al., 2018). High yield of heavy oil fractions, such as tar, have been reported at low temperatures ranges (300-400°C); thus, necessitating use of an energy intensive high temperature (Ramirez-Canon et al., 2018). Several studies reported in the literature supported high yield of lighter oil fractions and value-added gas fractions (such as CO, H_2, CH_4, etc.) between the temperature range of 400 and 600°C (Kan et al., 2017). However, other studies reported that the reactor configuration, feed type, and particle size also determine the level of dependence of liquid yield on temperature (Osayi et al., 2014). Some researchers reported that simple volatile compounds such as oil, plasticizer and additives, and moisture were released during thermal degradation of waste tyres at lower temperatures (220-250°C) (Ramirez-Canon et al., 2018). High volume of liquid fractions were reportedly obtained from the decomposition of styrene-butadiene-rubber at higher temperatures (400-500°C), but lower volume recovered from the butyl rubber (Ramirez-Canon et al., 2018). From the economic point of view, pyrolysis has not been commercialized in most advanced economies because of low volumetric yields (RMA, 2009). Therefore, its application in Nigeria may not be of potential interest to investors in energy and materials recovery from waste tyres, except on a laboratory scale for research purposes.

Another technology of interest to manage solid municipal waste and waste tyres disposal, is waste incineration. Incineration technology, using incinerators,

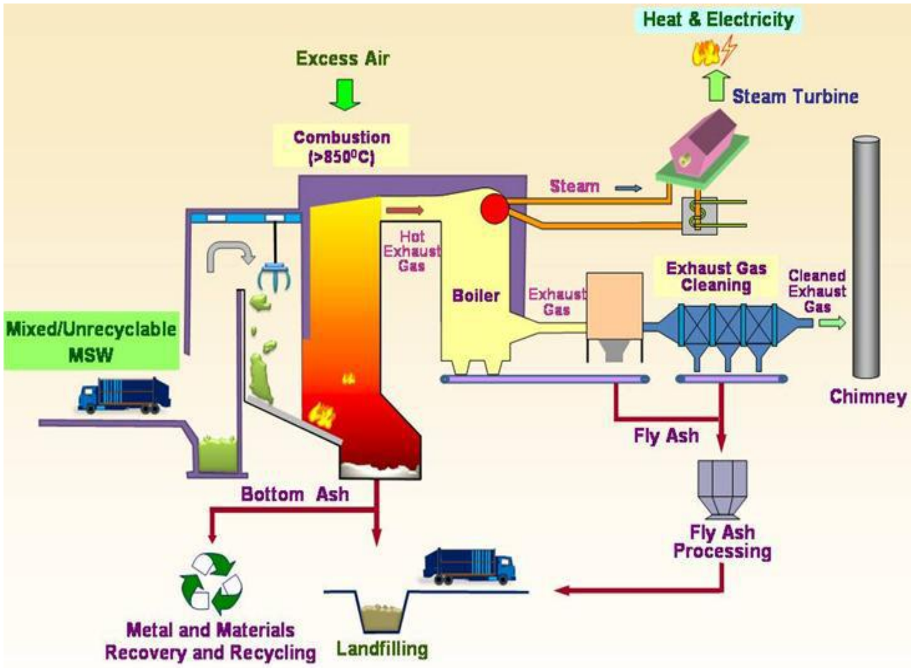

Figure 4. Schematic diagram of municipal solid waste (MSW) incinerator.
Source: Lam et al. (2010).

Figure 5. Waste incinerator at Petroleum Training Institute (PTI), Effurun, Nigeria.

has been deployed to manage waste successfully in countries such as Japan and Sweden to recover energy for heat and electricity generation (Figure 4 shows a typical example of an incinerator) (Lam et al., 2010). For instance, a pilot-plant waste incinerator (Figure 5) manufactured by INCINCO UK Limited, and installed at the Petroleum Training Institute, Effurun, Nigeria, has been used at a demonstration-scale level to showcase the benefit of incineration as a solid-waste management technology in Nigeria. Major products recovered from the process such as bottom ash and fly ash (used after pre-treatment to remove heavy metals, salts, chloride, organic pollutants, etc.) are sources of chemicals and valuable compounds such as CaO, SiO_2, Fe_2O_3, and Al_2O_3. These compounds could find applications in Nigeria, especially in the cement and concrete factories, ceramic industry, stabilizing agent, adsorbents and zeolite production. Most cement factories produce CaO from the thermal decomposition of $CaCO_3$ generating large emission of CO_2, a greenhouse gas (GHG) contributing substantially to global warming. Therefore, the production of CaO through combined waste (tyre, solids, etc.) incineration is considered environmentally friendly, as the process produces nitrogen, phosphorus, and potassium from the ash, for fertilizer production (Lam et al., 2010).

With the expansion of economic activities in Nigeria, the networks of roads across the six geopolitical zones are in deplorable conditions. Waste tyres can be shredded into crumb rubber and processed through ambient grinding or cryogenically turbo-milled (Lehigh technologies) to produce very fine micro-particles of free flowing rubber materials known as micronized rubber powder (MRP). Studies have shown that MRP can be efficiently and economically used as rubberized-asphalt concrete when mixed with conventional aggregate materials for road construction (RMA, 2009). MRP utilized in road pavements results in the followings:

(1) longer lasting and enhanced road surfaces;
(2) reduced road maintenance;
(3) lower road noise;
(4) cost effectiveness over long term;
(5) shorter breaking distances;
(6) skid resistance and better tyre traction.

Kim and Burford (1998) observed that when MRPs of diameter between 100 and 200 µm were incorporated into uncured NR as a filler, a better modulus match exists between the crumb and matrix compounding; making MRP a better filler for tyre manufacturing. MRP can also be utilized in the production of roof coatings, moulded and extruded products, adhesives, asphalt, plastic resins, sealants, brake pads and brake shoes with enhanced properties. Other promising areas where MRPs could be applied include athletic and recreational facilities such as ground cover for sports (e.g. football fields), playing fields, running tracks, and children playground (RMA, 2009). Therefore, proper understanding and utilization of MRPs can result in significant and environmental benefits when this green technology is deployed in Nigeria to create a sustainable economy.

Conclusion

Natural rubber was one of the major export products that earned Nigeria much revenue in the 1960s. However, rubber production declined in the 1970s because of heavy inflow of revenue from crude oil sales. Recently, a Presidential Initiative on rubber cultivation, production and export approved by Nigeria government for a 12-year period (2006-2018) targeting expanding rubber cultivation to 360,000 ha intended to boost the revenue generation from the agriculture sector, yielded positive results as hectares of rubber cultivated increased to 371,775. This initiative was borne out of the need to diversify the economy and enhance the income of the small-scale rubber farmers that account for about 85% of natural rubber production. The initiative improved Nigeria's export of natural rubber from US$37 million in 2017 to US$41.8 million in 2018. The provision of high yield Nigerian hybrid rubber seedlings (NIG800 and NIG900 series) to the small-scale farmers across the entire rubber producing areas will ultimately boost the production of natural rubber in the future. In addition, the value-added synthesis gas from the rubber processing plants will meet the energy requirements of local communities where most of the plants are located and possibly in excess, if any, that can be transmitted to the national grid. Additionally, waste tyres that constitute environmental hazards and health problems to humans can be properly harnessed through pyrolysis to recover energy and useful hydrocarbon oil and gas as sources of chemicals for a variety of industries and research institutes. Solid wastes of natural rubber origin, which significantly include waste tyres, can also be co-incinerated efficiently to recover energy for heat and electricity generation. In addition, production of chemicals and valuable metallic oxides from pre-treated bottom ash and fly ash from the incinerators have significant technical applications in cement and concrete production processes, ceramic industry, adsorbents and zeolite production. Potential markets such as construction of road pavements, athletic and recreational centres, agric and horticultural applications, horse arena flooring, etc., exist in Nigeria for the use of micronized rubber powders (MRPs) sourced from waste tyre (crumbs), and may remain a single viable commercial route for large-scale reuse of abundant waste tyres. The overarching benefits of rubber production and exploitation in Nigeria on improved GDP, sustainability of locally-acquired material resources, the revitalization of the agro-industry, and improving the country's ranking amongst NR producers cannot be overemphasized owing to the numerous unquantified outcomes to the government and its citizens.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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