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Review

Evaluation of production practices and yield enhancing techniques on productivity of cashew (*Anacardium occidentale* L.)

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Summary

Introduction – **The high economic potentials of cashew (*Anacardium occidentale* L.) as a trade commodity has nothwithstanding been hampered by the universal low yield of the crop, a major production challenge that requires an urgent and drastic solution. Various research attempts to provide "High Tech" innovative approaches to increase production and productivity are yet to have meaningful impact. Nonetheless, traditional and cultural methods of improving and stabilizing yields have evolved through the years and would need standardization.** *Materials and methods* – **This paper reviews the important research gaps observed in the production practices, assesses the various biotic and abiotic factors that could contribute meaningfully to the immediate and future cashew production and productivity, and highlights important plant features to harness as potentials to further optimize crop development, crop management and economic output.** *Results and discussion* – **Different landraces of differing nut grades have been adopted for different ecological zones and these possess differing characteristics of crop growth, seed sizes, quality, and yields. Improving cashew growth and yields should commence at nursery stage for the selection of vigorous plants, use of dynamic population adjustment methods, control mechanisms for flowering, sex ratio adjustment and fruit set/retention, adoption of soil amendment methods for different soil types, incorporation of cropping system approaches to control weeds, and irrigation techniques for dry areas, and introduction of high grade varieties into production systems that will impact on the value chain, are those cultural practices that need appraisal.** *Conclusion* – **Optimizing cashew management practices can improve the economic, nutritional and industrial performances of this underutilized crop. Adoption of improved production practices will result in an increase in crop yield, accruable foreign exchange, and improved livelihood of growers, improvement in consumer healthy eating, and industrial evolution from increased production of processed nuts and overall higher output along the production value chain.**

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Significance of this study

What is already known on this subject?

- Cashew tree is a cash crop tree well adapted to tropical and subtropical zones.
- Plantations in Africa are mainly hold by small scale owners with low yield.
- The cashew nut world market is increasing due to its high nutritional and industrial value.

What are the new findings?

- High tech applied to large scale plantations in Brazil is not recommendable in Africa.
- A series of innovations along the commodity chain are evaluated in the focus of small scale farmers: the dynamics of population adjustment methods, control of floral sex ratio for higher fruit set/retention, and adoption of compatible cropping system approaches are potential means for improved productivity of the cropping systems and postharvest handlings.

What is the expected impact on horticulture?

- At research level: fill knowledge gaps and provide low tech adapted to small scale farmers.
- At policy level: support sustainable (fair and environment friendly) cashew production for both the domestic and the export markets.
- At production level: increase in crop yield, lasting impact on consumer healthy eating, reconciliation of the polarized views between intensive agriculture and the extensive organic production systems, improved livelihood of growers and overall higher output along the production value chain.

Keywords

Nigeria, cashew, *Anacardium occidentale*, crop management, cropping systems, postharvest management

Résumé

Évaluation des pratiques de production et des techniques d'amélioration du rendement sur la productivité de l'anacardier (*Anacardium occidentale* L.).

Introduction – **Le potentiel économique élevé de la noix de cajou (*Anacardium occidentale* L.) en tant que produit commercial est néanmoins entravé par le faible rendement global de la culture, un défi de**

production majeur qui nécessite une solution urgente et drastique. Diverses tentatives de recherche visant à fournir des approches innovantes « High Tech » pour augmenter la production et la productivité n'ont pas encore eu d'impact significatif. Toutefois, les méthodes traditionnelles et d'amélioration culturale et de stabilisation des rendements ont évolué au fil des années et nécessiteraient une standardisation. *Matériel et méthodes* – **Cet article passe en revue les grosses lacunes en matière de recherche observées à travers les pratiques de production, il évalue les divers facteurs biotiques et abiotiques qui pourraient contribuer significativement à la production et à la productivité immédiates et futures de l'anacardier, et met en évidence les caractéristiques végétales potentielles pour optimiser le développement et la gestion des cultures, et la production économique.** *Résultats et discussion* – **Diverses variétés locales de différentes catégories de noix ont été adoptées pour différentes zones écologiques et elles présentent des caractéristiques variées de croissance des cultures, de taille des graines, de qualité et de rendement. La sélection des plantes vigoureuses, l'utilisation de méthodes dynamiques d'ajustement de densité de population, les mécanismes de contrôle de la floraison, l'ajustement du sex-ratio et de la mise à fruit/éclaircissage, l'adoption de méthodes d'amendement des sols pour différents types de sol, l'adoption de systèmes de culture pour contrôler les mauvaises herbes et de techniques d'irrigation pour les zones sèches, et l'introduction dans le système de production de variétés améliorées qui auront un impact sur la chaîne de valeur, sont les pratiques culturales qui nécessitent une évaluation.** *Conclusion* – **L'optimisation des pratiques de gestion de l'anacardier peut améliorer les performances économiques, nutritionnelles et industrielles de cette espèce sous-utilisée. L'adoption de pratiques de production améliorées entraînera une augmentation du rendement des cultures, des devises étrangères et améliorera les moyens de subsistance des producteurs, améliorera la consommation saine des consommateurs et l'évolution industrielle d'une production accrue de noix transformées et d'une production globale plus élevée.**

Mots-clés
Nigéria, noix de cajou, *Anacardium occidentale*, conduite de la culture, systèmes de culture, gestion post-récolte

Introduction

The cashew tree (*Anacardium occidentale* L.) is a native of tropical America from Mexico to Peru and Brazil and of the West Indies as well (Kumar *et al.*, 2012), and it has become naturalized in coastal areas of many tropical countries (IBPGR, 1986). The cashew trees are distributed across tropical, sub-tropical and temperate regions in the world (Engels *et al.*, 2012), and are spread between latitudes 27° N in Southern Florida and 28° S of South Africa; and also in low latitude regions, near the equator, between the parallel 15° N and 15° S, in coastal areas, typically tropical South America, Africa and Asia (Gomes, 2010). The Anacardiaceae family has 76 genera divided into five tribes (Anacardiaceae, Dobineae, Rhoeae, Semecarpeae and Spondiadeae) covering about 600 species (Correia *et al.*, 2006). The family is rich in important secondary metabolites with varieties of interesting biological activities (Abu-Reidah *et al.*, 2015). Some other important species of Anacardiaceae include mango (*Mangifera indica*), pistachio (*Pistacia vera*), amra (*Spondia* spp.), pink peppercorn (*Schinus terebinthifolia*), marula nut (*Sclerocarya birrea*), and neotropical fruits (*Antrocaryon* spp.) (Saroj *et al.*, 2014). Twenty-one species of the genus *Anacardium* were identified through classical taxonomy (Barros, 1005). Among these species, *Anacardium occidentale* L. is the single cultivated and widely distributed (Johnson, 1973; Ohler, 1979; Mitchell and Mori, 1987), and represents 90% of cashew production in Brazil (Leite *et al.*, 2016).

Cashew orchards are of great importance for the social economy of many developing regions of the world (Azam-Ali and Judge, 2004; Hall *et al.*, 2007). The USDA/USHHS (2010) recommended between 217–332 kcal person^{-1} day^{-1} fruit consumption for a healthy lifestyle, indicating that there is great potential for growth in these fruit markets (Sthapit *et al.*, 2012). Among the edible nuts that are traded globally, cashew ranks third in world production. World trade in edible nuts has experienced relatively rapid growth, averaging about 2.7% year^{-1} since the early 1970s and increasing in value from US$ 1.94 billion in 1980 to US$ 2.84 billion in 1990 (United Nations Yearbook of International Trade Statistics) (Azam-Ali and Judge, 2004). Worldwide, trade in cashews exceeds US$ 2 billion and demand is increasing. Of the total world supply, 110,000 t that are traded on international markets, India (60%) and Brazil (31%) are major exporters (Azam-Ali and Judge, 2004). Among major factors that affect the trade and consumption of cashew kernels in world markets is competition from other tree nuts. Unlike almonds and pistachios that are grown in very large plantations and have steady prices year after year, nonetheless due to the fact that cashew cultivation is not organized on plantation scale in most producing countries, the year-to-year variation in cashew crop yield occurring as a regular feature results in wide price fluctuations for cashew kernels (Nayar, 1995). Although the tree will not produce fruit in areas of very low rainfall, nonetheless the edible young leaves and the wood are still valued (Chemonics International Inc., 2002), as they are fairly hard with a density of about 500 kg m^{-3} (Orwa *et al.*, 2009), being used as timber, firewood and in the production of charcoal (Catarino *et al.*, 2015). The bark and leaves are used in folk medicine (Konan and Bacchi, 2007).

World demand for cashew nuts has increased at a rate of about 4% annually from 2007 to 2011 (FAO, 2013; INC, 2013). The production of raw cashew nut (RCN) has grown from 0.29 Mt in 1961 to 2.60 Mt in 2013, registering an 804% increase with a compound annual growth rate (CAGR) of 4.13% (Cashew Handbook, 2014). The increase in the global production is due to the realization of the health and economic value of the crop. The ever-increasing global demand for cashew nuts as remarked by Adavi (2008) is because cashew kernels provide a predominantly unsaturated fat. The world leading countries in cashew production area and production in 2012 include India (923,000 ha for 613,000 Mt) (Kumar *et al.*, 2012), Brazil (764,500 ha for 231,000 Mt) (ITC Market Insider, 2013), Nigeria (366,000 ha for 836,500 Mt) (Adeigbe *et al.*, 2015). According to FAO the nine countries that account for 94% of the cashew land areas and 91% of the cashew production include India, Brazil, Nigeria, Indonesia, Guinea-Bissau, Benin, Vietnam, Cote d'Ivoire and Tanzania (Clay, 2013; FAOSTAT, 2017). In Nigeria, which is ranked as the largest producer in Africa, the estimated cashew nut export represents about 7–8% non-oil export earnings (Nugawela and Oroch, 2005). Its production has increased almost thirty-fold from 30,000 Mt in 1990 to 836,500 Mt in 2012, from an estimated land area of 366,000 ha (Nugawela and Oroch, 2005; Adeigbe *et al.*, 2015). The introduction of Brazilian cashew biotype with improved and desirable nut and kernel quality characteristics by CRIN has further increased the crop spread and popularity in Nigeria (Hammed *et al.*, 2007).

Cashew nut proteins are complete, having all the essential amino acids and 1 kg of the nut yields about 6,000 calories compared to 3,600 calories from cereals, 1,800 calories from meat and 650 calories from fresh citrus fruit (Nambiar, 1990). The cashew nuts are a valuable source of macro and micronutrients, such as protein (18 g 100 g^{-1}), fats (44 g 100 g^{-1}) and iron (7 g 100 g^{-1}) (USDA, 2015). The nut in essence contains 47% fat, 21% protein and 22% carbohydrate, and high levels of magnesium, zinc, copper, manganese and essential fatty acids (USDA, 2015). It also contains vitamins, especially thiamine (Ohler, 1979; Nandi, 1998). Inside the soft honeycomb of the shell, there is a valuable greenish-yellow viscous liquid called cashew nut shell liquid (CNSL) The cashew nut shell liquid (CNSL) is a unique source of naturally occurring long-chain hydrocarbon phenols and constitutes about 25% of the cashew weight (Mazzetto *et al.*, 2009), and 30–35% of the nut shell weight (Mazzetto *et al.*, 2009). The anacardic acid, the combination of phenolic, carboxylic, and a 15-carbon alkyl side chain functional group makes it attractive in biological applications or as a synthon for the synthesis of a multitude of bioactive compounds (Hamad and Mubofu, 2015).

Most of the genotypes in Africa have very low productive capacity, consequent upon the low yield per tree, thus Africa shares very low percentage of the world production of cashew, while also advances for improvement of African cashew are still slow. Cashew possesses high genotypic and phenotypic variability (Phillip and Unni, 1984), the out-breeding nature of the crop (Aliyu, 2005), may have been facilitating continual evolution of additional genetic resources in many agro-ecologies of Africa. Therefore, the poor stride in cashew improvement in Africa could be blamed on poor assessment and underutilization of available genetic resources of the crop. However, progress in the improvement of this crop species through conventional breeding methods has been hampered by a long gestation period needed to generate genetic materials with better performances (Adewale *et al.*, 2013).

Nevertheless, the challenge of low yield in African cashew trees remains daunting, and the major players in tropical agriculture still remain the poor peasant farmers with low input resources for latest technological practices, such as irrigation, storage and processing. The growing research focus into tree crop production requires governmental support at a higher pedestal than is presently obtainable. Nonetheless, that tree crop research faced with long gestation period would require that other means of improving yield and productivity through cultural practices, produce handling and value chain addition should be devised to raise the prospects of small-scale farmers engaging in the production. As earlier revealed by the research findings of Connolly *et al.* (2001) from experiments conducted on productivity indicators and methods of intercropping systems (IC), there is paucity of information on intercropping systems involving perennial fruit crops such as cashew (Olubode *et al.*, 2016a).

This article reviews the various aspects of cashew production that cut across the nursery stage, plantation stage, flowering and fruiting stages, soil amendment practices, cultural approaches to manipulating yield through population dynamics for yield stability, adoption of compatible crops for improved productivity of the cropping systems and postharvest handlings that have been researched with the expectation to explore those production and yield gaps that require further research.

Nutritional and economic potentials of cashew

Cashew nut is a complete food: the kernel which is a rich source of protein (21%), carbohydrate (22%) and fat (47%), also contains minerals such as Ca, P, Na, K, Mg, Fe, Cu, Zn and Mn. Cashew kernel lipids are also rich in unsaturated fatty acids such as oleic acid (73.7%), linoleic acid (7.67%) and stearic acid (11.2%) (Saroj *et al.*, 2014). Cashew kernels are observed to be free from cholesterol as it contains sizeable quantity of monounsaturated fatty acid (oleic acid) which is probably helpful in lowering down the blood cholesterol (Saroj *et al.*, 2014). Cashew kernel contains few vitamins like thiamine, niacin and vit. E (Ohler, 1979).

Cashew nut processing allows for the development of an important by-product, which can increase its added value, likewise every part of the tree is commercially useful as firstly, the bark which is used in tanning, or as an insecticide, in adhesive for book binding, as substitute for Arabic gum, and in making ink; secondly, the residue of the cashew apple when it is used to extract pectin; thirdly, the nut shell which is used in the cosmetic industry, pharmaceutical industry, textile industry, paper industry, and ink making (Opeke, 2005); fourthly, the cashew nut shell liquid (CNSL) which is used in preservation of boats, nets, and wood; in insulating varnishes and resins; in paint industry, particle board adhesives, thermo-plastic resins, thermosetting resins, and plastic industry. Lastly, the CNSL is of great commercial value as it is rich in phenol, one of the main input substances used in industries of plastic, varnish, insulating material, paint and automobile (Melo, 1998). The cashew shell produces oil which is also used as insecticide against mosquito larvae, and has uses as a waterproofing agent and as a preservative, but when distilled and polymerized, the oil is used in insulating varnishes and in the manufacture of typewriter rolls, oil- and acid-proof cements and tiles, brake linings of motor vehicles, paints, varnishes and laminated products (Murthy and Sivasamban, 1985). It is also used as a plywood adhesive (Akaranta *et al.*, 1996), and as a material for increased tensile properties, as flame retardants of natural rubber (Menon, 1997), and as a long-life, highly bioactive, anti-fowling coating for marine vessels (Panda and Panda, 1991).

Distillation of the light yellow oil from cashew nutshell yielded 74% cardanol, 10% phenolic compounds and 15% alkyl benzenes (Lin *et al.*, 1991; Shobha *et al.*, 1992). Natural anacardic acids have been found to be potent antibacterial relatives to salicylic acid, although their activity is limited mainly to gram-positive bacteria (Himejima and Kubo, 1991). Natural cashew nut liquid is non-genotoxic, whereas technical liquid is genotoxic in prokaryotes and eukaryotes, although there is no evidence of their mutagenic effects on eukaryotic cells. The excellent antioxidant and non-mutagenic activities of cashew nut shell liquid (CNSL) provide opportunities for CNSL in the cosmetic and/or pharmaceutical industries (Leite *et al.*, 2016). In addition, the tree is evident for its antioxidant (Melo-Cavalcante *et al.*, 2003), antigenotoxic, antimutagenic (Melo-Cavalcante *et al*., 2011), anti-ulcerogenic (Behravan *et al*., 2012), anti-inflammatory (Olajide *et al*., 2004), antibacterial, antifungal and larvicidal activities (Carrara *et al*., 1984; Evans and Raj, 1988; Echendu, 1991; Weerasena *et al*., 1993; Behravan *et al*., 2012). The CNSL liquids have antifungal, antibacterial, antiparasitic, anti-tumor, anti-ulcerogenic, molluscicidal, antimutagenic and antioxidant activities (Himejima and Kubo, 1991; Casadei *et al*., 1984; Kubo *et al*., 1986). The main markets for CNSL are the United States, the European Union (mainly the United Kingdom), Japan and the Republic of Korea. Together these account for over ninety percent of world trade, most of which is supplied by India and Brazil (Azam-Ali and Judge, 2004).

Environmental potentials of cashew as bio-indicator

Morphologically, the architecture of cashew tree makes it a foremost tree crop for reclaiming land area to enhance productivity, through the prevention of desertification and soil erosion (Adeigbe *et al*., 2015). Cashew was originally used in Africa in afforestation schemes or as a fire protection barrier around forest demarcations (Goujon *et al*., 1973; Behrens, 1996; Orwa *et al*., 2009). The cashew considered as a waste land crop, whose productivity is unaffected with or without improvement on its immediate environment, nonetheless flourishes in soils where most other crops fail (Ohler, 1979), thus fueling the initial erroneous belief that the crop would not need nutritional assistance for enhanced productivity. However, cashew as a result of its wide adaptation is often grown in very poor soils and this has affected its survival and establishment (Topper *et al*., 2001). Further research on the wide adaptation has shown the environmental capability of the tree as a bio-indicator that could have potential use in phytoremediation of polluted environments. In this regard, various plants have been used as bio-indicators to assess the impact of different sources of environmental pollution (Onder and Dursun, 2006). Hyperaccumulators are those plants that can absorb high levels of contaminants concentrated either in their roots, shoots and/or leaves (Ghosh and Singh, 2005). Among the plants studied for the phytoremediation of metals as possible bio-indicators of heavy metals to remove pollutants from the environment included the use of Neem (*Azadirachta indica*), cashew (*Anacardium occidentale*), and mango (*Mangifera indica*) trees (Raskin *et al*., 1997). The potency of cashew as bio-indicator was determined and ranked as Mango > Cashew > Neem in that order of magnitude describing the plants' uptake efficiency of heavy metals (Ojekunle *et al*., 2014). Although other metals were not evaluated, the Brazilian variety was reported to have higher Fe uptake compared to other cashew varieties (Olubode *et al*., 2016b), thus indicating differential nutrient Fe uptake by cashew varieties. Nonetheless, seedlings fumigated with SO_2 at 1–3 h in polyethylene chambers showed sensitivity evidenced by leaf injury and loss of chlorophyll (Padhy *et al*., 1994). These reports showed that despite the hardiness of the cashew to environmental hazards, there are areas of tolerance and susceptibility of cashew plant indicating the limitations to usefulness in phytoremediation.

Vegetative growth

The pattern of growth – potentials to crop development

The four types of cashew trees include the dwarf, common, giant and wild cashew (Mitchell and Mori, 1987; Barros *et al*., 1998; Masawe, 2009), although two main types that are known include the large trees and dwarf cashew (Araujo, 2013). Each of the four groups can also be categorized into three sub-groups based on branching patterns which could be extensive, intermediate and intensive branching (Masawe, 2009). Only large trees are cultivated in most producing areas compared to dwarf cashew trees (Catarino *et al*., 2015), while the medium sized trees (semi-dwarf) have been developed through natural crossings or controlled hybridization (Masawe, 2009). Compared with tall trees, the semi-dwarf trees showed no difference at 2 months, but at 8 months seedlings were shorter with shorter internode length than those from tall trees (Nayak *et al*., 1995). Trees with extensive branching patterns appear to be low-yielding while those with intensive to a large extent appear to be high-yielding. In high-yielding trees more than 60% intensive branches are seen whereas low-yielders possess less than 20% intensive branches (Masawe, 2009). The 'intensive shoot' grows to a length of about 25–30 cm and ends in a panicle, while in the 'extensive type', the shoot grows to 20–30 cm length and rests. Concurrently in the intensive type that tends to give bushy appearance to the tree, 3 to 8 lateral shoots come up below 10–15 cm of the apex and few of these laterals may also bear panicles. On the other hand in the 'extensive type', a bud sprouting 5–8 cm below the apex gives rise to further growth which continues for two or three years without giving flowers and results in spreading tree habit (Masawe, 2009).

The cashew tree in some cases can reach a height of 5–10 m, but in clay land can reach up to 20 m with a crooked trunk of 25–40 cm in diameter. The cashew develops well in temperatures varying from 22 to 40 °C, although the ideal average temperature for normal development and fruit bearing is 27 °C (Parente *et al*., 1972). The influence of altitude on temperature notwithstanding, cashew plantations may be found at altitudes up to 1,000 m close to the equator; however at higher latitudes and altitudes above 170 m, the yield is negatively affected (Aguiar and Costa, 2002). The characteristics of the tap and lateral roots are of importance in relation to the fertilization of cashew (Crisóstomo *et al*., 2007). The root distribution pattern depends on soil type (topography, soil texture, stoniness and the presence of a hardened soil layer), planting material and method, age, level of crop nutrition, and irrigation (Falade, 1984; Dendena and Corsi, 2014).

The leaves are oval, obovais, leathery, glabrous; rosy when young; it has vinaceous flowers, arranged in terminal panicles (Lorenzi, 2008). Leaves reached their full size 25 days after emergence but maximum photosynthesis (*P*n), stomatal conductance (g), and chlorophyll (ch) content occurred 7 weeks after leaf emergence. The leaf longevity was approximately one year while chlorophyll content began to decline 46 weeks after leaf emergence (ALE) (Schaper and Chacko, 1993). Net photosynthetic rate could be measured after 8 days of development (Balasimha, 1991), and though leaves reached full size 25 days ALE, maximum photosynthesis (P_N), stomatal conductance (g) and chlorophyll content (chl) occurred 7 weeks ALE (Balasimha, 1991). Net photosynthetic rate (P_N) was much lower in the shaded leaves than in sun lit ones, and this was linearly related with stomatal conductance and transpiration rate. The competition for radiant energy was more important than any other single environmental variable for the photosynthetic capacity (Balasimha, 1991).

Light saturation of photosynthesis of mature leaves occurred at approximately 1,200 µmol photon m^{-2} s^{-1} PPFD. Dark respiration (Rd) decreased during the first 5 weeks ALE. In the presence of developing fruit or leaves, the source leaves in girdled branches maintain a high rate of gas exchange as long as those sinks were increasing in size. In the absence of a sink, branch girdling resulted in a rapid and marked reduction in gas exchange of the source leaves (Schaper and Chacko, 1993). There was no significant difference in P_N between leaves at various positions in a single flush but which was much lower in the shaded leaves than in the sunlit ones, and was linearly related with stomatal conductance and transpiration (Balasimha, 1991). The distribution of N was 21.1, 22.2, 20.93, 15.37 and 20.4% in leaves, stem, wood, bark and root, respectively, the corresponding figures for P were 21.5, 29.15, 19.94, 13.21 and 16.2% and for K were 18.94, 18.61, 24.42, 14.43, and 22.7% (Reddy and Reddy, 1987). Trunk starch levels were at their highest after the dormant winter period, and at their lowest following the harvest (Roe, 1994). Starch levels in the roots, dry matter production in the leaves, roots and stems, as well as leaf area were decreased significantly with increasing low temperature duration (Roe, 1994).

Plant leaf area is an important determinant of light interception and consequently of transpiration, photosynthesis and plant productivity (Goudriaan and Van Laar, 1994). Leaf area is an important variable for most ecophysiological studies in terrestrial ecosystems concerning light interception, evapotranspiration, photosynthetic efficiency, fertilizers, and irrigation response and plant growth (Blanco and Folegatti, 2005). Moreover, ecologists use leaf area relations for elucidating competition among different plant species (Harper, 1977). Leaf area estimate is valuable in studies of plant nutrition, plant competition, plant-soil-water relations, plant protection measures, respiration, light reflectance, and heat transfer in plants (Mohsenin, 1986), and thus it is an important parameter in understanding photosynthesis, light interception, water and nutrient use, and crop growth and yield potential (Smart, 1974; Williams, 1987). A rapid non-destructive method involving maximum length and maximum breadth gave the best prediction equation:

$$A = (0.8356)\ L^{0.843}\ B^{1.08}$$

with R^2 as high as 98.92% to estimate leaf area in cashew based on linear measurements of leaf. However, it could be preferable to use a less cumbersome linear model:

$$A = 0.21 + 0.69\ P \quad (R^2 = 96.81\%)$$

where P is the product of length and breadth of leaf (Murthy *et al.*, 1985). The 3 or 4 central leaves, depending on an odd and even number of leaves, on the shoot irrespective of the size of the shoot can be regarded as the representative leaves, and for quicker estimate, the median leaf or 2 central leaves could be considered representative for leaf area measurement (Bhagavan and Mohan, 1988).

Propagation methods

Vegetative propagation methods

Cashew can be propagated by seedlings, air layers and softwood grafts. Since it is a cross-pollinated crop, vegetative propagation is recommended to obtain true-to-type progeny (Asogwa *et al.*, 2008). Propagation methods using seedlings present great variation in growth habit, quality and yield of nuts (Chipojola *et al.*, 2013). Establishing new orchards of cashew through vegetative propagation is of great importance as it improves maintenance of genetic integrity of the genotypes as well as shortens the juvenile period of the tree (Lenka *et al.*, 1993). Dipping the cut end of the scion in wax before storage had an average grafting success of 44.95% after 6 days storage while the un-waxed scion though with comparable grafting success stored for up to 3 days (Lenka *et al.*, 1993). Mature scions demonstrated superiority over the immature scions due to their ability to withstand adverse weather conditions (Chipojola *et al.*, 2013). Field establishment of air layers have been found to be poor, hence softwood grafts, which give a high rate of establishment and early flowering, are recommended for planting. The few notable differences showed that xylem is well developed in seedling root while parenchyma is well developed in air layers roots and vice versa (Melanta *et al.*, 1989). The highest survival (97.5%) obtained in air layers rooted with 300 ppm IBA and hardened in sand + red earth + coir dust (1:1:1 v/v), and higher survival of air layers in all medium with coir dust indicated that root growth and field establishment of air layers were influenced by the porosity and water holding capacity of the medium (Shetty and Melanta, 1990). In the midst chamber, 49.72% of cuttings from 4-month-old seedlings rooted, their survival rate was 100% and the number of roots per cutting ranged from 4.5 with no regulator to 15.3 with NAA at 100 ppm, and the length of the longest root ranged from 8.5 cm with IAA at 500 ppm to 17 cm with IBA 2,000 ppm (Melanta and Sulladmath, 1990). Using soft wood graft (Lenka *et al.*, 1991) and soft wood and veneer graft (Pugalendhl *et al.*, 1992) as scion material (Lenka *et al.*, 1991; Pugalendhl *et al.*, 1992), beheading at 0.5 m above ground level produced the best results in terms of plant survival and percent graft success in rejuvenation of over 10-year trees. Cuttings treated with IBA at 10,000 ppm rooted only when prepared from bark-ringed shoots, while the response to ringing declined with increasing age of trees (Rao *et al.*, 1987, 1988). Micropropagation of cashew has been attempted using explants from both juvenile and mature tree origin with success being registered in explants of juvenile stage (Boggetti *et al.*, 1999).

Seed propagation methods

Although, direct seeding (Adenikinju *et al.*, 1989; Adenikinju, 1996), as well as early transplanting of cashew seedlings (Adeyemi, 2000), were suggested as ways of reducing mortality of cashew seedlings after transplanting into the field, direct seeding results in wastage of improved seeds during planting (Esan, 1981; Adenikinju *et al.*, 1989; Adu-Berko *et al.*, 2011), and usually good, mature large or jumbo-sized nuts sundried to a moisture level of 8.5% are recommended for plantation establishment. The sinkers gave 98% germination, while the floaters gave 87%, indicating the inappropriateness of soaking methods in germination test (Adeyemi and Hammed, 2003). Irradiation of seeds treated at 0, 10 or 20 kR obtained highest percent germination (97.5%) with a decline at 60 kR, while irradiation at doses 10–20 kR stimulated seedling growth whereas doses at 40 kR induced dwarfism (Salam *et al.*, 1991). Nonetheless, cashew with large nut size had good seedling growth characteristics (Adebola *et al.*, 1999), and possesses initial seedling growth advantage over that of small-sized nuts (Ibiremo *et al.*, 2012). Seeds which matured 40 days after fruit set had the lowest 100-seed weight (339 g) compared to seeds which matured in 60 days that had the highest 100-seed weight (538 g) (Renganayaku and Karivaratharaja, 1993). Newly emerging seedlings should be grown under approximately 45% shade in the nursery and hardened off in sunlight before final planting. Nursery stage premature cotyledon abscission coupled alongside the transplanting shock observed in cashew

(Hammed and Olaniyan, 2012), and corroborated by earlier reports on premature cotyledon abscission in cacao (Atanda, 1971), might be responsible for the reduced morphological plant performance of seedling transplants. This corroborates earlier report by Haugen and Smith (1993), that cotyledon removal reduces cashew plant growth, and irrespective of the portion removed either the half or total removal resulted in significant retardation to seedling growth compared to those with intact cotyledon (Olubode *et al.*, 2017).

Reproductive growth

Transition between the vegetative and reproductive phases

Cashew is an evergreen dicotyledonous woody tropical tree with medium-size canopy, and a pattern of growth that alternates between the vegetative and reproductive phases. The initiation and duration of these growth phases vary among varieties as these phases are regulated by both genetic and environmental factors (Saroj *et al.*, 2014). Cashew trees start bearing fruit after a 2–4 year gestation period and continue to produce for 25–30 years, while the dwarf varieties have a gestation period of 1–2 years and also produce for over 20 years (Chemonics International Inc., 2002). In general, seedling cashew plant starts flowering in three to five years while grafted trees come to flowering within three years. The flowering normally starts at the end of cold season after the emergence of new growth flush, but its timing and duration are strongly influenced by temperature (Damodaran *et al.* (1965), as cited in Saroj *et al.* (2014). In cashew the fruit set and development is dependent on irradiance and the adaption of leaf to shade is minimum (Subbaiah, 1984), nevertheless shading can result in shift in flower types produced, indicating temperature effects on sex ratio (Foltan and Lüdder, 1994).

Flowers are produced at the end of the new shoots. Thus, flowers and fruit are borne on the outer extremity of the canopy [Damodaran *et al.* (1965) as cited in Saroj *et al.* (2014)]. The cashew requires relatively dry atmosphere and mild weather (15–20 °C minimum temperature) coupled with moderate dew during night for profuse flowering. High temperature (> 34.4 °C) and low relative humidity of less than 20% during afternoon causes drying of flower resulting in yield reduction (Saroj *et al.*, 2014). The growth monitoring of cashew seedling revealed that active cell division and elongation contributed to the linearly continuous growth of cashew (Hammed *et al.*, 2011). Starch levels in the roots, dry matter production in the leaves, roots and stems, as well as leaf area were decreased significantly with increasing low temperature duration (Roe, 1994). The quantitative values of protein did not differ much between the vegetative (v) and reproductive (r) phases. Total amino acids decreased during the transition while sugar and starch contents increased. Total starch slightly decreased and the phenolic content increased markedly in the r phase. The dry matter percentage (DW%) was also high due to increased tissue differentiation in the r phase (Sherlija and Unnikrishnan, 1996).

The dry matter production by a wide range of annual and perennial crops has been linearly related to accumulated-light interception (Palmer, 1989). Many field crops form continuous layers where light interception is approximately an exponential function of LAI, however the scope for canopy manipulation is relatively small and tends to be confined to genetic manipulation of leaf angle or proportion of photosynthetic tissue in different photosynthetic organs (Palmer, 1989). Further dimension of variation in lead canopy occurs in row crops where such factors as row orientation, spacing, plant height and spread are all variables which, along with leaf area, influence light interception (Palmer, 1989).

Flowering behavior in perennial fruit crops

Flowering in fruit trees is an important reproductive phenomenon which marks the beginning of fruit production. The flowering phase is comprised of four stages starting with flower induction, flower initiation, flower differentiation, and blooming. At present there are two models that explain flowering in perennial fruit crops, one regulated by carbohydrates and another by hormones (Ravishankar *et al.*, 2014). Firstly, is the regulation by carbohydrates brought about by accumulation of photo-assimilates and its redistribution during each annual production cycle, where the interactions between the accumulated carbohydrates and putative floral stimulus triggers floral induction (Chacko, 1991), and thus explains the biennial bearing feature where flower initiation is strongly limited by excessive crop during 'on' years, resulting in low yields and sometimes even no fruit, in 'off' years (Monselise and Goldschmidt, 1982). Secondly, is the role of phytohormones, such as auxins, cytokinins and gibberellins, that indicates that there is a relationship between a putatively cyclically temperature-regulated floral stimulus produced in leaves, an age-dependent floral inhibitor residing in leaves and fruits, and bud activity during floral cycle (Kulkarni and Rameshwar, 1989; Davenport, 2003; Ramírez *et al.*, 2010; Ramírez and Davenport, 2010, 2012).

In most tropical climates for economic levels of flower bud induction, a stress of 2–3 months duration is required (Davenport, 1990; Albrigo and Sauco, 2004), however, floral intensity (flowers per shoot) increases with accumulated low temperatures, and could diminish with the presence of crop load and the occurrence of high temperatures (Albrigo and Sauco, 2004). The cashew requires some stress to synchronise flower induction, where for instance in climates with two dry periods, cashew flowering may take place twice a year (Roe, 1994). Under normal circumstances, cashew trees that are not irrigated have two peaks of flowering (Ohler, 1979; Northwood, 1966). There are some exceptions where cashew trees may have only one peak of flowering (due to drought) or can flower continuously when under irrigation (Barros *et al.*, 1984; Bezerra *et al.*, 2007). Flowering occurred after the wet season during the driest and coolest period of the year (Wunachit and Segley, 1992). However, flowering in perennial plants is complex and under regulation by several gene networks (Ravishankar *et al.*, 2014).

Floral biology of cashew

Unlike the mango, which bears its crop on the past season's wood, the cashew produces flowers on the current season's flushes (Roe, 1994), after the growth flush at the end of the rainy season. However, some trees develop terminal inflorescences without any previous shoot growth (Ohler, 1979). As regards flowering, three types of cashew trees exist, early, middle and late flowering. Development of the flowering panicle starts with production of new flushes. Flushes may grow vegetatively or reproductively, depending on the phonological phase of the growing tip or shoot (Masawe and Kapinga, 2010). Cashew flushes may vary in shape, size and color depending on the genotype (Masawe, 2006). Some cashew varieties are easily identified by the type of leaves or flushes. Reddish, pinkish, greenish or intermediate color flushes are most common (Masawe, 2006).

The cashew is andromonoecious or polygamous, with male and perfect or hermaphrodite flowers being found on the same panicle of a cashew plant. The indeterminate panicle may be conical, pyramidal or irregular in shape (Kumaran *et al*., 1976; Thimmaraju *et al*., 1980), however, abnormal flower types have also been reported (Northwood, 1966; Fernandes and Fernandes, 1969; Purseglove, 1974; Kumaran *et al*., 1976; Agnoloni and Giuliani, 1977; Joseph, 1979). The number of panicles per plant, flowers per panicle and distribution of male and hermaphrodite flowers (sex ratio) in each panicle vary significantly, with an average observed ratio of 6:1 staminate to perfect flowers (Bigger, 1990; Masawe *et al*., 1996), and less than 40% of hermaphrodite set fruit followed by a high rate of a premature fruit drop (Saroj *et al*., 2014). The hermaphrodite and male flowers were similar in structure, except that the male flowers lacked a pistil and were smaller than the hermaphrodite, where male flowers have one large stamen (an anther and a filament) and several small stamens. Abnormal flowers are like male flowers but they do not have a large stamen. Hermaphrodite flowers have both large and small stamens, and in addition they have the female parts (stigma and styles) (Masawe and Kapinga, 2010). In most cases, the first flowers to open are male and abnormal flowers, followed by hermaphrodite flowers (Masawe and Kapinga, 2010).

There were significantly tree-to-tree differences in the length of flowering period, number of hermaphrodite and male flowers, the proportion of hermaphrodite flowers, the number of fruit set, the number of fruit shed, and the number of mature fruits, but there were no year-to-year or within-tree differences (Wunachit and Segley, 1992). The average numbers of days to flower bud development among different varieties depend on the genotype and environmental conditions and ranged between 23.6 and 28.8, and the duration of flower opening may range from 46.5 to 66.1 days, while the mean number of flowers produced per panicle was 442.9 of which 7.3% were hermaphrodite, the remainder being male (Heard *et al*., 1990; Schaper and Chacko, 1993). The anthers are basifixed, bilobed and dehiscent between the two pollen sacs of each lobe. The anther is rounded and pink coloured turning grey at dehiscence (Northwood, 1966; Ohler, 1979; Nair *et al*., 1979; Moncur and Wait, 1986).

Flowering in cashew is usually profuse; about 85 to 90% of the shoots of a bearing tree flower every year (Saroj *et al*., 2014). The mean duration of flowering was measured as 84.4 days in which the duration of the first male phase was 2.4 days, the mixed phase 69.4 days and the second male phase 13 days (Roe, 1994). Flowering appears in two or three distinct phases; (i) the first male phase with 19 to 100% male flowers; (ii) the mixed phase with nil to 60% male flowers and nil to 20% hermaphrodite flowers; and (iii) the second male phase with nil to 67% male flowers. In most cases, the first flowers to open were male (Pavithran and Ravindranathan, 1974). In the anthesis, flower opening started before 6 h and continued until 16 h. The peak period of opening of perfect flowers was 9–10 h in all the genotypes studied while anther dehisces peaked between 8–10 h (Chattopadhyay and Ghosh, 1993). Anthesis proceeds basipetally in the panicle, flowers in the younger branches opening first. A gradient in sex ratio at successive nodes of a panicle existed, the percentage of perfect flowers increasing from the proximal to the distal end (Ashok, 1979; Subbaiah, 1983). Cashew trees require 4, and even 5 months to complete the sequential anthesis in the panicle (Pavithran and Ravindranathan, 1974).

Although pollination was not a limiting factor for cashew production (Heard *et al*., 1990), the number of hermaphrodite flowers can be used as a selection criterion (Wunachit and Segley, 1992), while it was observed that the male flowers, rather than hermaphrodites, determine the yield potential (Masawe *et al*., 1996). Cashew flowers are self-fertile, but probably not self-pollinating, as bagged flowers set no fruit but self-pollination by hand-improved fruit set (Masawe, 1994). Nonetheless, the presence of scent, nectar, coloured petals and sticky pollen all suggest insect pollination (Masawe *et al*., 1996). Receptivity of the flowers began one day before anthesis and lasted about 2 days, with an optimum period soon after anthesis. Anthesis occurred from 1 to 5 h after the flowers opened, depending considerably on temperature. Anthesis occurred more rapidly with flowers opening in the heat of the day than with those opening early in the morning (Northwood, 1966). It was also found that flowers opened earlier on the sunny side of the tree (Damodaran *et al*., 1966; Saroj *et al*., 2014). Pollen remains viable for two days (Ohler, 1979).

Fruit setting

Poor fruit set and a high rate of premature fruit abscission are the major restrictions to yield (Foltan and Ludder, 1995). Maximum fruit set was obtained within the first 3–4 weeks of the fruiting period, while fruits from flowers opening later were usually shed indicating a competitive advantage of the first fertilized and most advanced fruits (Foltan and Ludder, 1995). The cashew produces abundant flowers but only less than 10 per cent of which are hermaphrodite, about 85% of the hermaphrodite flowers are fertilized under standard conditions and only 4–6% of them reach maturity to give fruits, the remaining shed away at different stages of development. The fruit drop in cashew during the early stages of development is attributed to physiological reasons (Northwood, 1966). Insect attacks also play an important role in immature fruit drop (Pillay and Pillai, 1975). Although cashew plants can permit about 27% of their well-pollinated flowers to develop into fruits, in the wild only 10.5% yield is possible (Reddi, 1987).

Yield precocity is dependent upon both precocity of flowering and the ability of those flowers to set, retain, and size fruits (Webster, 1995). The quality of a flower which is the ability to set and retain fruits, is mainly determined firstly, by the viability and longevity of its ovules, secondly, by the receptivity to pollen of the stigma, and thirdly, by the synchrony of development of the flower organs (Webster, 1995). These three factors can, however, be modified by the age of wood and type of flower bud (axillary, spur, or terminal), where the axillary flowers formed on 1-year-old wood open later than spur or terminal shoot flowers and have shorter "effective pollination periods" (EPP), that is the number of days after anthesis (flower opening and pollen release) during which the flower remains capable of setting fruit in response to pollination with viable pollen, while also weather conditions during floral development may influence fruit set (Webster, 1995).

Crop growth requirements

Light interception is defined as the difference between the irradiance above the canopy and the mean irradiance beneath the canopy, expressed as a fraction of above-canopy irradiance or an accumulated total over a per unit area basis but can be calculated on a per unit tree or length of row. The absorbed light does not include light reflected from the canopy (Palmer, 1989). The cashew tree is a sun-plant and does not grow well under conditions of excessive shade. Although leaves at the east quadrant recorded highest leaf area of 120.4 cm^2 (Lakshmipathi *et al.*, 2014), production was more favorable on the sunset side than on the sunrise side, net photosynthesis rate (P_N) was maximum in leaves on all sides of a tree (east, west, south and north) between 11:00 and 12:00 a.m.; between 3:00 and 4:00 p.m. photosynthetic active radiation (PAR) and P_N were higher in leaves on west side than in other directions. Maximum P_N occurred in leaves of the middle portion of the tree rather than at the top or bottom (Palanisamy and Yadukumar, 1993). The appropriate texture of soil should be loam or sandy loam with a very slightly acidic to neutral pH (pH = 6.3–7.3). As the soil type varies considerably with depth, texture and other physical and chemical properties, it is difficult to classify soils/lands according to their suitability for cashew crop (Nair *et al.*, 1979).

Nitrogen application has the greatest effect of increasing yield when applied during the vegetative growth stage, which was shown to reduce late flowering and nut drop (O'Farrell *et al.*, 2010), while phosphorus and sulphur applications were proven to positively affect plant growth and nut production (Grundon, 1999). Although, the nutrient removal from the soil, due to fruit and pseudo-fruit harvesting, should be factored into planning fertilizer application (Dendena and Corsi, 2014), hence, the application of 500 g N, 125 g P_2O_5, and 125 g K_2O tree^{-1} annually in two split doses is recommended when assuming an annual average nut yield of 5–10 kg tree^{-1} (Panda, 2013). As NPK rate increased, the duration of harvesting time and the total percentage of harvested nuts increased significantly while harvest season became earlier, moreover the percentage of export grade kernel (210 and 240 counts) increased by the high NPK and growth regulators (Kumar *et al.*, 1995). The critical concentration of N and P in relation to yield were 2.09 and 0.14% as observed in fully matured leaves (Kumar and Sreedharan, 1987). Moreover, larger yields of cashew nuts were obtained with a combination of N, P_2O_5, and K_2O equivalent to 200, 75, and 100 g plant^{-1} year^{-1}, respectively (Ghosh and Bose, 1986), while the application of 250, 125, and 125 g plant^{-1} year^{-1} of N, P_2O_5, and K_2O, respectively was reported as suitable for significantly increasing the yield of 15-year-old cashew plants (Subramanian *et al.*, 1995). Moreover, manure in the form of cow dung and poultry dropping contain other macro-and micro-nutrients like calcium and magnesium, which are not available from inorganic sources and acts as slow release for nitrogen, thus limiting leaching and acidification and may improve soil structure and water content (Ipinmoroti *et al.*, 2011).

Moisture availability to plants is an important soil or land quality that is relevant in a wide variety of circumstances (FAO, 1976). Soil moisture is a key variable of the climate system. It constrains plant transpiration and photosynthesis in several regions of the world, with consequent impacts on the water, energy and biogeochemical cycles (Seneviratne *et al.*, 2010). However, it is influenced by many factors which include soil texture, soil depth, soil structure and temperature (Israelsen and Hansen, 1962). Moisture varies spatially as well temporarily due to different factors influencing it, such as land characteristics of a given area (Gómez-Plaza *et al.*, 2001), rainfalls, potential evapotranspiration, available water capacity of soil and soil type which all affect moisture availability to crop growth (FAO, 1976). The upslope contributing area, aspect, and soil profile curvature and soil depth best explained the spatial variability of the soil moisture content in the vegetated zone. The actual influence of these factors showed marked seasonal variations due to changes in the physiological activity of the vegetal cover (Gómez-Plaza *et al.*, 2001).

Field production practices

Seedlings raised in medium and small sized bags are easier to be conveyed at planting time, however large polybag size produced more vigorous plants in the field (Adu-Yeboah *et al.*, 2015) while for optimum growth and high survival rate, transplanting cashew seedlings between 4 and 8 weeks after seeding (WAS) was observed to have high plant stands (Hammed and Olaniyan, 2012). Successful field establishment occurs when seedling leaves are halved and roots pruned before planting (Adu-Yeboah *et al.*, 2016), and root pruning prior to planting not only improves the establishment of overgrown seedlings but stimulates root growth and root fibrosity which is of benefit to out-planting survival (Andersen *et al.*, 2000), and improves root-soil contact needed for adequate water and nutrient absorption for plant growth (Geisler and Ferree, 1984; Grossnickle, 2005).

The unique management and horticultural practices include grafting, pruning, training, spraying and harvesting strategies, all designed to maximize productivity and orchard efficiency. In training and pruning of young and established cashew (including pruning of deadwood and dry branches, crisscross branches, intermingled branches, vigorous shoots and sprouts, and leader shoots in older plantations), precautions are required while pruning and the economic benefits (increased yield) of pruning were observed (Nayak, 1996). Lack of pruning, weeding, fertilizer application or pest control which are important factors required in the improvement of the productivity are among causes of significant negative impact on the productivity of the cashew tree (Tolla, 2004). Statistically significant differences were observed for pruning, weeding and fertilizer application types of crop management (Guimarães Callado, 2009). Shading led to enhanced formation of hermaphrodite flowers, while exposure to sunlight resulted in a shift towards differentiation of male flowers, indicating temperature effects on sex ratio (Foltan and Lüdder, 1994).

Pruning is carried out once a year, usually after the seasonal fruiting to train cashew to a single stem by allowing branches to grow to about 0.75–1.00 m from ground level and at a height of 4–5 m by topping off the main stem (Asogwa *et al.*, 2008), to allow the growth of a uniform canopy and avoid overcrowding, to which cashew plants are particularly sensitive (Dendena and Corsi, 2014). Pruning of trees can promote protection against diseased and infected branches (phytosanitary pruning), although cautioned to be limited during the first year of growth (Ohler, 1979; Nathaniels *et al.*, 2003), pruning practice is very important for fruit trees mainly aiming at obtaining higher yields and indispensable to get the desirable shape of the tree for improved agricultural management. Yield, which in turn is partially driven by prices since favorable prices tend to make farmers more willing to invest in tree maintenance activities (Fynn, 2004), is highly sensitive to care and good practices such as proper pruning and application of fertilizer and sulphur to avoid fungal infections (UNIDO, 2011). The putative floral stimulus is reported to possess a life span of 6–10 days and is transported via phloem along with photo-assimilates from the leaves to receiving buds (Davenport, 2006, 2007; Ramírez *et al.*, 2010).

Irrigation frequency is one of the sources of water available to plant growth; excessive volumes of water in a soil retard plant growth and make drainage essential. Under typical drought situation cashew suffers in term of yield, but it does not die due to its inherent drought tolerance nature (Bezerra *et al.*, 2007). Although cashew trees tended to alternate years of high nut yield and years of low yield, even when irrigation was applied (Oliveira *et al.*, 2006), yield increases have been demonstrated from supplemental irrigation (Moncur, 1988) with highest nut yield obtained with accumulated pan evaporation of 10 mm. For good production of cashew, the rainfall level must be around 900–1,100 mm annually and also must be evenly distributed over the 9–10th month of its growing season (Mole, 2000). Irrigation allows maximum productivity, increasing the harvest period and improving the quality of the peduncle and the nut, and could increase productivity by up to 300% (Crisóstomo *et al.*, 2007). Irrigation water depth at 400 to 500 L tree^{-1} weekly equivalent to 30 L m^{-2} of canopy silhouette area was calculated for 5-year-old trees grown under high evaporating demand in sandy soils (Richards, 1993b). Daily watering to field capacity and all manure application rates with optimum at 5 t ha^{-1} favored improved growth responses in cashew seedlings compared to unfertilized control, while the Brazilian variety was poorly adapted to moisture stress compared to the Jumbo and local varieties (Olubode *et al.*, 2016b).

The wide space between rows of cashew trees has been used in cropping systems for planting subsistence crops such as cassava, beans and fruit crops. The weeding time depends on the age of the tree (Guimarães Callado, 2009). In fertilizer application methods, the highest nut yield (5.902 kg tree^{-1} year^{-1}) was obtained when applying NPK in a circular band 1.5 m wide covering 1.5–3.0 m from the trunk, followed by two circular trenches of 1.5 m and 3.0 m from the trunk (5.391 kg tree^{-1} year^{-1}), and in a broadcast application over the entire area up to the drip line (4.306 kg tree^{-1} year^{-1}), compared with applying a single trench along the drip line control (3.782 kg tree^{-1} year^{-1}) (Radhakrishna *et al.*, 1993; Sutramanian *et al.*, 1995).

Population dynamics in yield stability of cashew

Rootstocks may influence both the floral precocity, either directly or indirectly by their effects on scion branching, and the quality of flowers produced including their ability to set and retain fruitlets (Webster, 1995). The control of tree size is critical for the optimization of productivity and for limiting the amount of labor and inputs needed for orchard management which utilize dwarfing rootstocks and/or inter-stocks to control tree size (Suzuki *et al.*, 1988; Webster, 1995; Atkinson and Else, 2001). Smallholders farm production showed large variation in relation to local tree density and canopy ground cover ratio (CGCR) where maximum production occurred at tree density equivalent to 40–80 trees ha^{-1} and CGCR 0.5–0.6. Individual tree yields were poorly correlated with density and CGCR, but were highly correlated with their yield in previous year, indicating that tree yields were consistent from year to year. The smallholder farm productivity therefore may be improved by a combination of selective thinning of poor-yielding trees and the planting available spaces with improved materials (Martins and Kasuga, 1995). The recommended plant spacing for cashew is 7.5 × 7.5, 8 × 8 or 9 × 9 m, which gives a density of 175, 156 and 123 trees ha^{-1}, respectively. High-density planting is a recent technique recommended for enhancing early productivity of cashew plantations (Asogwa *et al.*, 2008). Planting of more numbers of seedlings at 4 × 4 or 8 × 4 m, which gives a density of 625 or 312 trees ha^{-1}, respectively, can be retained for a period of 6 to 7 years depending on the canopy expansion rate be-

FIGURE 1. A multi-branching cashew tree, enabling easier crop management through planting density.

fore selectively thinning them down. High-density planting in poor soils helps to effectively control weed growth in the inter-space, gives higher yields at early growth stages, and substantial quantities of firewood during thinning, which may fetch additional revenue to the farmers.

The intentional use of population dynamics in tree crop orchard management for yield enhancement has been employed in most modern plantations in fruit producing regions. The adoption of a higher plant density for young trees that are later thinned at matured stage to wider spacing of lower population provides the benefit of a higher initial cumulative yield from the higher plant density. This could be achieved, firstly, by the use of dwarfing rootstocks, secondly by the use of dwarfing hormones, and thirdly by the use of inoculum of exocortis viroid as dwarfing agents. Moreover, controlling plant size has been an important goal for years in many plant species (Costes and García-Villanueva, 2007). In fruit tree industries, tree vigour is mainly controlled by dwarfing rootstocks, which are widely employed in intensive orchards to restrict tree volume and promote earlier flowering (Lockard and Schneider, 1981; Barritt *et al.*, 1995; Fallahi *et al.*, 2002). The widespread use of dwarfing rootstocks in the fruit-tree industry, their impact on tree architectural development based on tree architectural plasticity in response to its root system has a possible role in the within-tree balance between growth and flowering (Costes and García-Villanueva, 2007), and on the number of long shoots while flowering potential depends on the cultivar.

In the high-density plantation of fruit crops, controlling tree vigour and canopy size are important for enhancing the orchard efficiency and productivity without causing injury to plants (Umar and Sharma, 2008). Out of several strategies suggested, use of rootstocks and chemical growth retardants has been found to modify growth, development and increased yield in a number fruit crops (Umar and Sharma, 2008). The responses varied with chemical, rate of application, timing, cultivar and vigour (Umar and Sharma, 2008). Thus tree height can be controlled by two ways; first, the physiologically based technique which includes use of root stocks, scion, cultivar and tree density, and second, the horticultural control methods which include irrigation methods, crop load adjustment, fertilization practices, pruning technique and chemical growth regulators (Umar and Sharma, 2008).

Plant bio-regulator includes both naturally occurring plant hormone as well as synthetic chemical substances which have hormonal effects when exogenously applied to plants (Hartmann *et al*., 1997). Plant growth retardants are widely used in agricultural industry (Zhou *et al*., 2014), to control tree vegetative growth (Davis *et al*., 1991; Basak, 2000; Medjdoub *et al*., 2004), and have important impact on the economic production of fruit crops by incorporating more trees in a given area of land because of their reduced tree height, canopy size and spread, resulting in increased fruit yield at the expense of only cost of chemicals and its cost of application (Umar and Sharma, 2008). Significantly lower growth rates, and early panicle production, higher mean yield was obtained for plants treated with paclobutrazol (PP 333) at 500 to 2,000 mg L^{-1} (Misra and Singh, 1991; Roe, 1994), applied ethephon at 500 and 2,000 mg L^{-1} resulted in excessive leaf drop, disturbed the rootshoot balance and normal phenological patterns, and gave poor yields, while urea at 2% concentration gave a significant increase in flushing and simultaneous decrease in flowering (Roe, 1994).

Most of the growth regulators act as gibberellic acid (GA) biosynthesis inhibitors among which four different types of GA inhibitors are known: firstly, 'Onium compounds' including chlormequat chloride, chlorphonium and AMO-1618 (2-isopropyl-4-dimethylamino-5- methylphenyl-1-piperidinecarboxylate methyl chloride); secondly, 'N-containing heterocyclic compounds' including hexaconazole (HX), ancymidol, flurprimidol, tetcy-clasis and paclobutrazol; thirdly, 'acylcyclohexanediones' including prohexadione-calcium (Pro-Ca), trinexapac-ethyl (TNE) and daminozide; fourthly, '16, 17-dihydro-GA5 and related structures' (Rademacher, 2000). Nevertheless, the persistence in the plant of chemicals such as daminozide, ethephon and paclobutrazol as un-metabolized form have raised concern due to the residue toxicity and health risk (Smit *et al*., 2005), while novel class of plant growth regulators such as Pro-Ca, TNE and HX show lack of persistence in plant. Application of Pro-Ca reduces the length of stem internode and vegetative growth of fruit trees such as apple (Ratiba and Blanco, 2004), pear (Smit *et al*., 2005), and cherry (Jacyna *et al*., 2012). The short-term effect of these chemicals provides a flexible tool for vegetative growth management that can be applied at different times and growth strategies (Evans *et al*., 1997).

Alternatively, genetic variability can be induced by mutagenizing agents, such as chemical and physical mutagens to produced Induced Mutations (Ahloowalia *et al*., 2004; Henikoff *et al*., 2004). The technique has potential for modifying existing traits or creating new valuable traits within the cultivated varieties (Predieri and Virgilio, 2007). Hence, in almost all of the main temperate and tropical fruit species, breeding efforts have resulted in selection of dwarf scions or dwarfing rootstock varieties (Busov *et al*., 2003), resulting in commercially acceptable dwarf varieties which allow dense field cultivation, increased harvest index and a substantial decrease in production costs (Costes and García-Villanueva, 2007; Foster *et al*., 2014). Although not in frequent use, the exocortis viroid identified and first reported as a disease in some of the important citrus rootstock varieties (Fawcett and Klotz, 1948), has the advantage of being extremely resistant to both high temperatures and dry conditions and can remain ineffective for long periods of time until infestation occurs (Hardy *et al*., 2008). The important point is that only the vegetative plant parts are affected but the plant genetic attributes that determines the yield responses are unaffected.

The "dwarfing effect" is complex and most likely regulated by a number of signalling pathways acting in tandem rather than in isolation (Atkinson and Else, 2001). These smaller trees produce fruits to be hand-picked for the fresh market, and are also easier to target with sprays, thereby reducing undesirable spray drift and increasing efficiency of spray usage (Webster, 2004). Rootstocks may influence the number of flowers on a tree through changes in scion architecture, particularly with respect to branch angle (orientation) and shoot development, and may also induce increases in the number and size of flowering spurs on older wood. Fruit on dwarfing rootstocks also tends to be larger (Atkinson and Else, 2001). Rootstocks can influence the vigour, habit and cropping of the scion cultivar, as well as its resistance/tolerance to soil or aerial borne pests and diseases and to unfavourable climatic or edaphic conditions (Webster, 2004). The increased yield efficiency on dwarfing rootstocks may in itself be partly explained by improved flower quality and reduced competition between young fruitlets and extension shoot growth (Webster, 2004). Closer planting of more dwarfed trees in the orchard should more than compensate for the reduction in yield per tree compared to those from larger trees on intermediate or vigorous rootstocks (Webster, 1995).

Also, in studies on grafted rootstocks, shoot vigour was found to be positively correlated with rates of cytokinin export from roots to the scions of grape (Skene and Antcliff, 1972), apple (Kamboj *et al*., 1999) and peach (Sorce *et al*., 2002). In addition, shoot vigour was shown to be negatively correlated with the amounts of auxins moving basipetally in the scions of grafted peaches (Sorce *et al*., 2002). Roots subjected to drought or other stresses, which cause reductions in shoot growth, also exhibit lower levels of cytokinin production and export (Vaadia and Itai, 1968; Torrey, 1976). This indicated the possible combined influences of auxins and cytokinins in the action of dwarfing rootstocks, and the possible influence of other plant bio-regulating chemicals such as abscisic acid and gibberellins, which have also been implicated in the dwarfing mechanisms (Robitaille and Carlson, 1976). The floral inhibitors are proposed to be gibberellin or gibberellin-like compounds (Yeshitela *et al*., 2004). Those treatments that encourage the formation of gibberellin may encourage growth, those that discourage growth encourage flowering.

Fertilizer use in crop productivity

'Conventional or intensive farming' utilizes Green Revolution methods designed to maximize profit, often by extracting maximum output using external purchased inputs, especially mineral fertilizers and synthetic agro-chemicals and irrigation to support production, while 'organic farming' is a certifiable farm management system (with controls and traceability) that is in harmony with the local environment using land husbandry techniques such as soil-conservation measures, crop rotation and the application of agronomic, biological and manual methods instead of synthetic inputs, and the 'traditional farming' is often subsistence-oriented, using few or no purchased inputs (IFAD, 2005). Without the use of synthetic fertilizers, world food production could not have increased at the rate it did and more natural ecosystems would have been converted to agriculture (Tilman *et al*., 2002). Nonetheless, in the tropical environment like Nigeria, the quest to optimally increase crop yield with fertilizer use has not been attained as a result of lack of adequate fertilizer recommendation because fertilizer usage are mostly based on blanket application (Ogunlade *et al*., 2011), hence crop production is still constrained by too little application of fertilizers (Tilman *et al*., 2002), while soil testing programmes do not take into account the amount of nutrient being fixed by the soils (Ogunlade *et al*., 2011). Most vegetated lands have undergone human-induced soil degradation and loss of productivity, often from poor fertilizer and water management, soil erosion and shortened fallow periods (Oldeman, 1994). Continuous cropping and inadequate replacement of nutrients removed in harvested materials or lost through erosion, leaching or gaseous emissions deplete fertility and cause soil organic matter levels to decline, often to half or less of original levels (Matson *et al*., 1998).

Nonetheless, the detrimental environmental impacts of agricultural practices are costs that are typically unmeasured and often do not influence farmer or societal choices about production methods (Tilman *et al*., 2002). However, environmental considerations play a major part in strategies relating to agriculture whether at the level of the individual company or global institutions. Although, the use of hybrid seed, irrigation, and agrochemicals to fuel intensive farming are methods that have in a few short decades become embedded in the educational, policy, and extension systems of most countries (Shiva, 1992; IFAD, 2002, 2004). Nonetheless, when switching from intensive forms of agriculture to organics, labour costs are higher, input costs are lower, yields may be reduced and overall income is higher, the switch to organics from traditional cultivation methods tends to increase labour costs but has eventual positive consequences in terms of yields and provides better incomes for traditional producers (IFAD, 2005). Measuring total farm yields is more appropriate than measuring single crops since some diversification away from single cash crop production is characteristic of organics. In many cases, organic systems are more profitable than conventional ones and more than make up for reduced yield or productivity that may occur during transition, primarily due to price premiums (IFAD, 2005). The reconciliation of the polarized views between intensive agriculture and the extensive, organic systems with the new way forward being sustainable crop production intensification recognizes that high-input systems using commercial seed, fertilizer and crop protection chemicals are necessary but that at the same time they should be used judiciously with every attempt made to minimize their adverse environmental impact (KPMG International, 2013).

Organic agriculture builds soil quality and is generally less water-intensive than conventional agriculture, it can be particularly productive where conventional farming would be impractical or too costly (IFAD, 2005). The water-holding capacity of soil can be increased by adding manure or reducing tillage and by other approaches that maintain or increase soil organic matter. Cultivation of crops with high water-use efficiency, and the development – through the use of biotechnology or conventional breeding – of crops with greater drought tolerance can also contribute to yield increases in water-limited production environments (Charles, 2001; DeVries and Toenniessen, 2001). Soil tillage speeds decomposition of soil organic matter and the release of mineral nutrients. The effects of land degradation on productivity can sometimes be compensated for by increased fertilization, irrigation, and disease control, which increase production costs (Naylor, 1996). Although, cashew grows very well on wide range of soils irrespective of their textural, structural and fertility status, its survival and establishment however is often affected by poor soils (Topper *et al*., 2001). Moreover, under favourable flowering conditions cashew yield was markedly affected by soil, pH and Ca status of the soil (Richards, 1993a). Compared to low-input farms, the use of mineral fertilizers in the plantation-based farm was responsible for the major impacts on human toxicity, acidification and eutrophication (Figueirêdo *et al*., 2014). Although the amount of pesticides used can be decreased with intercropping systems (IC) that increase biodiversity in cashew orchards (Xavier *et al*., 2013). The higher yield efficiency measured by nut density crop load allowed a greater portion of soil and tree nutrient to be allocated to nuts. More research on improving efficiency and minimizing losses from both inorganic and organic nutrient sources is needed to determine costs, benefits and optimal practices.

Inorganic fertilizer in crop production

Applying fertilizers during periods of greatest crop demand, at or near the plant roots, and in smaller and more frequent applications all have the potential to reduce losses while maintaining or improving yields and quality (Cassman *et al*., 1993; Peng *et al*., 1996; Matson *et al*., 1996, 1998). Such 'precision agriculture' has typically been used in large-scale intensive farming, but is possible at any scale and under any conditions given the use of appropriate diagnostic tools (Tilman *et al*., 2002). Cashew crop requires regular fertilizer application, particularly from fruit set onward (Nair *et al*., 1979), the combined application of potassium and phosphorus is indispensable in the first stages of cashew growth (Parent and Albuquerque, 1972), and regular application of nitrogen, potassium and phosphorus is beneficial for obtaining healthy trees and increasing cashew yields (Azam-Ali and Judge, 2001). NPK application, preferably monthly from postharvest flush, should be applied at regular intervals. Meneses Junior *et al*. (1993) observed that fertilizer application increase tree vigour with best response obtained under highest NPK rate (288:432:192 g plant^{-1}) but no significant response was observed for individual rate of N, P or K. With P_2O_5 and K_2O at 200 and 400 g plant^{-1} year^{-1}, respectively, the weight of the nut, number of nuts, height and vigour of the plants were increased and reached a maximum with 600 g N plant^{-1} year^{-1} (Ghosh, 1990). Substantial increases in nut production with the application of up to 288 g P and up to 176 g S plant^{-1} year^{-1}, during three consecutive years was found, for 4-year-old plants, but there was no increase in yield from applying up to 3,000 g K_2O plant^{-1} year^{-1} (Grundon, 1999). Treatments with $ZnSo_4$ increased the total sugars and ascorbic acid content and acidity of cashew apples at all stages of development but had little effect on the lipid content of the kernel, while kernel protein was increased by the 5% treatment (Roy and Mazumbar, 1989). Among treatments application of NPK 500:250:250 g plant^{-1} and spraying with ethrel at 500 ppm were not effective, however application did not significantly influence fruit weight and juice content but juice total soluble solids (TSS) and fruit yield per tree increased significantly (Kumar *et al*., 1996). A negative correlation was observed between leaf N, P and K and sugar and fruit juice and a positive correlation with juice percent and ascorbic acid content (Kumar and Sreedharan, 1987).

Organic cashew production

Organic produce is a fast-growing US$ 27-billion segment of the food industry and is increasingly drawing the attention of farmers, governments and development agencies (IFAD, 2005). There were 43.7 Mha organic agricultural lands in 2014, including conversion areas, and currently one percent of organic agricultural lands in countries covered is organic (Willer and Lernoud, 2016). Organic farming as a systematized and certifiable approach to agriculture is a relatively new phenomenon. It is no surprise that its adoption faces some challenges among both farmers and the public sector. Policymakers tend to be polarized in their views of organic farming; they see it either as a very lucrative modern niche or as a traditional and perhaps backward approach used by the poorest farmers. This interesting dichotomy reflects the somewhat different experiences and approaches taken in different countries (IFAD, 2005).

Consumers today are becoming increasingly conscious of the health and nutritional benefits of the food they consume, and there is an increasing tendency to avoid the consumption of chemically treated foods. Indigenous fruits can play an important role in satisfying the demand for nutritious, delicately flavored and attractive natural foods of high therapeutic value (Rolle, 2006). The total organic cashew estimated imports in Europe at 2,000–2,500 Mt year^{-1} is about 3.25% of all cashews imported. The prices for organic cashews across the globe are usually 20–25% above the price for conventional cashews. In a survey 43% of respondents agreed that organic produce were more wholesome than conventionally grown ones and 33% were prepared to pay 23–27% premium on different organic produces (Dipeolu *et al*., 2009). Although when prices for all cashews rise dramatically, the organic premium declines from 25 to 10–15% (Cambodia Agribusiness Series, 2010).

Organic agriculture is a viable approach that can be suitable for smallholders, and can be particularly useful in the more difficult environments, where resources are scarce and cultivation is problematic, but also potentially serves to reduce risk by encouraging localized input production, fostering soil and water conservation and encouraging the diversification of production (IFAD, 2005). Most tropical cashews are organic by 'default' in that the natural evolution of cashew production did not require, and farmers could not afford, agro-chemicals (Cambodia Agribusiness Series, 2010). Cashews are called the 'poor farmers' crop' because they are largely grown by subsistence farmers who plant a few trees to earn cash for household necessities such as health care and fuel. Hence subsistence farmers are usually good candidates for organic certification because they cannot afford agro-chemical inputs such as fertilizer and pesticide. However, because most farmers let cashew trees grow with low inputs, pruning or other effort, cashew yields are low and so are farmers' earnings. Cashew yields and their selling price can be improved significantly if farmers apply organic fertilizer, manage trees, correctly using pruning and organic pest control, and improve harvest and post-harvest practices (Cambodia Agribusiness Series, 2010). Although, it is estimated that 70% of the world cashew production is organic, but only a tiny fraction of it is certified. Nevertheless, the area which remains organic by default is declining as chemicals and fertilizers are introduced (Cambodia Agribusiness Series, 2010).

Organic fertilizer and bio-fertilizers in cashew crop production

Organic agricultural practices include the use of cover crops, manures, compost, crop rotation, intercropping, and biological pest control utilizing non-synthetic nutrient-cycling processes that exclude the use of synthetic pesticides, to sustain, or regenerate, soil quality (Badgley *et al*., 2007). Sustainable intensification involves the use of the best available technologies and inputs such as best genotypes, best agronomic management practices and best postharvest technologies to maximize yields, while at the same time minimizing or eliminating harm to the environment (El-Ramady *et al*., 2015). Organic agriculture also has the potential to provide benefits in terms of environmental protection, conservation of non-renewable resources, improving food quality and the reorientation of agriculture towards areas of market demands (Odeyemi, 2013). Recent meta-analyses have revealed that the "yield gap" of organic agriculture to conventional agriculture is 19–25% (Seufert *et al*., 2012; Ponisio *et al*., 2015). However, yield differences are highly contextual, depending on cropping system and site characteristics, and range from 5% lower yields in organic agriculture (rain-fed legumes and perennials) to 34% lower yields (Seufert *et al*., 2012). With good management practices, particular crop types such as legumes, fruits and perennials can result in organic yields comparable to conventional yields. Ponisio *et al.* (2015) indicate that the 19% "gap" may be an overestimate. However, more research and innovations are needed to increase yields in organic agriculture, both in developed and developing countries, to safeguard food security and ensure low levels of global environmental impacts, such as GHG emissions (Knudsen *et al*., 2010). Furthermore, while decision makers and public institutions affecting the future of organic agriculture often base their decisions on simple yield comparisons and environmental impact assessments relative to conventional systems, holistic and multi-criteria systems analyses will be required to guide organic agriculture as well as conventional agriculture towards improved sustainability.

Organic agriculture according to definition by the International Federation of Organic Agriculture Movements relies on ecological processes, agrobiodiversity, cycles adapted to local conditions, and agro-ecological approaches (Niggli *et al*., 2008). Therefore, eco-functional intensification with improved nutrient cycling techniques and agro-ecological methods for enhancing diversity and health of soils, crops and live-stock is a priority in organic agriculture. In addition, eco-functional intensification is based on the knowledge of stakeholders; it relies on powerful information and decision-making tools and the cooperation and synergy between different components of agriculture and food systems (Niggli *et al*., 2008). Subsequently, the Royal Society awakened the principle of "sustainable intensification" (Pretty, 1997), which they define as agriculture where yields are increased without adverse environmental impact and without the cultivation of more land. Later, Bommarco *et al.* (2013) developed the principle of "ecological intensification" into entailing the environmentally friendly replacement of anthropogenic inputs and/or enhancement of crop productivity, by including regulating and supporting ecosystem services management in agricultural practices, which do not differ from the principles of eco-functional intensification.

In organic agriculture, which often may have greater environmental variability than in intensive conventional agriculture, yield advantages through the competitive production principle often occur (Vandermeer, 2011). Crop species may complement one another in both time and space when species differences give rise to a better overall use of resources in intercrops than in the separate sole crops (SCs). Sustainability is a factor determining acceptability, or otherwise, of a specific production practice which encompasses conservation of non-renewable resources (soil, energy, minerals) and addresses environmental and social sustainability (Lampkin, 1990). Although manures are usually bulky, and the cost of transporting them is high, manure is described as being a safer source of nutrients, which are released in a steady manner over time to crops which encourages soil microbial activities (Eifediyi and Remison, 2010). Often abundant in cities are many organic waste and by-products, including municipal waste, which may become environmental pollutants but which possess considerable nutrient value that can be used as organic manure (Lu *et al.*, 2011). Application of organic fertilizers from city waste and sourcing these due to the benefits accruing from their use are on the increase in recent times.

Manure sustains cropping systems through better nutrient recycling and improvement in soil physical, chemical and biological properties. Use of manure has been recommended for long-term cropping in the tropics as the slow mineralization of manure promotes crop yield over a long period (Ojeniyi, 2000; Gambo *et al.*, 2008), and increases soil water holding capacity making the nutrients more readily available to crops (Dada and Fayinminnu, 2010). When practiced on long duration, direct and indirect effects of organic agriculture could contribute to better crop yield on a sustainable basis compared to conventional production. The application of 2.5 t ha^{-1} cocoa pud husk would effectively and steadily facilitate a linear increase in cashew stem diameter within the first 24 months of field establishment, however, beyond 2.5 t ha^{-1} it resulted in a declining trend (Akanbi *et al.*, 2013). Continuous nutrient addition to cashew varies with genotypes, age and the soil nutrient status (Opoku-Ameyaw and Appiah, 2000; Bezerra *et al.*, 2007; Hammed *et al.*, 2011; Ibiremo *et al.*, 2012). Although poultry dung manure and cocoa pod husk ash were significantly better than cow dung manure, and kola pod husk ash, where total dry matter yield of cashew seedlings were increased by 62.07, 56.21, 44.1 and 38.08%, respectively, optimal and sustainable growth performance of cashew seedlings was attained by the use of organic fertilizer materials especially those of poultry dung manure and cocoa pod husk ash which were thus observed as good alternative compared to the total dependence on costly and scarce chemical fertilizers (Akanbi *et al.*, 2013).

The application of bio-fertilizer arbuscular mycorrhizal fungi (AMF) that readily form association with cashew roots (Haugen and Smith, 1993), has potential to enhance crop production (Fagbola *et al.*, 2001). Arbuscular mycorrhizal fungi biotrophically colonizing cashew were found to enhance plant growth by improving phosphorus nutrition (Ananthakrishnan *et al.*, 2004; Lakshmipathy *et al.*, 2004). Since cashew easily forms association with native mycorrhizae in the soil, inoculation of cashew with exotic AM may not be necessary (Ibiremo *et al.*, 2012). Inoculated plants grew less well than non-inoculated ones, possibly as a result of changes in pH following inoculation/infection. There were no positive effects of inoculation on nutrient concentration in plant tissue, except for increased K concentration in the leaves and roots of inoculated plants (Haugen and Smith, 1993). Cotyledon removal reduced the negative effect of inoculation on plant growth, although it reduces plant growth in both inoculation and non-inoculation treatments (Haugen and Smith, 1993). Root temperature was associated with marked differences in the morphology and growth of the root system: with poor root growth of cashew at 38 °C, *Gigaspora intraradices* remained ineffective. Indeed, *G. intraradices* can remain in moist soil at high temperature but the extent to which the plant becomes infected depends on the host factor such as root growth (Haugen and Smith, 1992). Nonetheless, phosphate fertilizer, nut sizes and AM inoculation significantly ($P < 0.05$) enhanced the total N, P, K, Ca and Mg uptake of cashew seedlings (Ibiremo *et al.*, 2012).

Maximizing production and productivity in cashew

Total nut yield tree^{-1} in cashew is influenced by genetic factors, cultural practices and climatic factors, however, nut yield was controlled by five characters (number of reproductive shoots, number of bisexual flowers per panicle, fruit set, fruit retention and total number of nuts produced tree^{-1}) (Kumar and Udupa, 1996). A density of 62.5 trees ha^{-1} was sufficient to provide a threshold level for maximizing productivity on a unit area basis (Balasimha and Yadukumar, 1993), and although 92% of the trees flowering in their third year, the average global yield of cashew nut (605 kg ha^{-1}) is about 55% of that of selected clonal material under good management conditions. Average yields tree^{-1} increase from 3 kg at ages 3–5, to 4 kg at ages 6–10, 4.7 kg at ages 11–15 and 5.3 kg from 16–20 year-old-trees. Cashew responds well to fertilizer application, especially during the vegetative growing period (Hammed *et al.*, 2011). The response of cashew trees to mineral nutrients application in most cases is significantly dependent on plant age, the genotype, conditions of cultivation (soil and climate), other management schedules, etc. (Foltan and Lüdder, 1994; Ibiremo *et al.*, 2012). The present low productivity per hectare of cashew is mainly attributable to the use of non-descript varieties, low quality planting materials, non-adaption of recommended package of practices and others (Aliyu, 2005). Furthermore, the low yield in cashew can also be attributed to lower percentage of perfect flowers, low fruit setting and poor fruit retention. Thus, there is a great gap between the average yield harvested and the potential yield that cashew crop is capable of producing under optimum growth conditions (Lakshmipathi *et al.*, 2014). The vegetative and reproductive growth of trees depends on assimilate production which is controlled by tree architecture and leaf functions, both modulated by environmental interactions (Lakso, 1994).

Recent agricultural practices that have greatly increased global food supply have had inadvertent detrimental impacts on the environment and on ecosystem services, highlighting the need for more sustainable agricultural methods, hence the use of cover crops or reduced tillage can reduce leaching, volatilization and erosional losses of nutrients and increase nutrient use efficiency (Tilman *et al.*, 2002). Crop rotation, reduced tillage, cover crops, fallow periods, manure use and balanced fertilizer application can help maintain and restore soil fertility (Tilman *et al.*, 2002). Reliance on organic nutrient sources is a central feature of organic agriculture (Drinkwater *et al.*, 1998), but it is unclear whether the 'slow release' of nutrients from organic compost or green manures can be adequately controlled to match crop demand with nutrient supply to increase nitrogen-use efficiency in intensive crop production systems, thereby decreasing losses to leaching and volatilization. Strategies that synchronize nutrient release from organic sources with plant demand are therefore also needed (Woomer and Swift, 1994; Robertson, 1997).

Ethrel had significant influence on leaf area production (Lakshmipathi *et al.*, 2014), while 50 ppm ethrel and 25 ppm NAA resulted in highest nut yield (kg) tree^{-1}. Increased nut yield with application of growth regulators could be attributed to increased number of bisexual flowers, fruit set, fruit retention and total number of nuts tree^{-1} (Veeraraghavathatham and Palaniswamy, 1983), and may be due to increased concentration of photosynthesis in the shoot (Nunez *et al.*, 1998; Zoffoli *et al.*, 2009; Zahoor *et al.*, 2011) as reported in grape. Konhar and Mech (1988) reported highest fruit retention in cashew with 500 ppm nutron (triacontanol), followed by 50 ppm ethrel (ethephon) and 45 ppm planofix (NAA). Similarly, Kumar *et al.* (1994) found ethrel at 50 ppm, NAA at 25 ppm and 2,4-D at 4 ppm to be most effective in improving sex ratio and yield. Ethrel at 100 ppm significantly increased the number of flowering panicles m^{-2} (12.0), the number of perfect flowers $panicle^{-1}$ (52.8), the fruit-set m^{-2} (28.8), the number of nuts $panicle^{-1}$ (2.9) and the yield (1.51 kg $tree^{-1}$) compared with the control and water spray (Gawankar *et al*., 2010). Among the applied ethrel and CCC or TIBA and 2% KNO_3, ethrel at 50 ppm resulted in the highest nut yield followed by 1,000 ppm CCC (Mohan and Rao, 1995). The highest percentage fruit retention (25.8) was obtained with nutron at 500 ppm, followed by ethrel at 50 ppm (25.4%) and planofix at 45 ppm (22.8%) compared to control (7.28%) (Konhar and Mech, 1988). Application of planofix to cashew had the most significant effect ahead of ethrel in causing a reduction in the number of male flowers per panicle and in increasing the number of hermaphrodite flowers per panicle and also in significantly increasing both the number of nuts per shoots and weight of nuts per shoot (Mariappan *et al*., 1995). Auxin activity in cashew increased during the 180 days after ringing (Rao *et al*., 1990).

Harnessing the benefits of cropping systems

The wide space between rows of cashew trees has been used in cropping systems for planting subsistence crops such as cassava, beans and fruit crops. The weeding time depends on the age of the tree (Guimarães Callado, 2009). Appropriate management practices usually considered in cropping systems include three important factors of optimum production potential, input efficiency, and environmental protection for a specific site in order to ensure a better sustainable basis (Tolla, 2004; Griffith, 2001). Crop productivity depends on crop's developmental pattern and various physiological processes in response to its management and its environment. Usually also most traditional farm holders in tropical regions have accepted the inter-cultivation of tree crops with early yielding crops species as standard and as appropriate method to profitably utilize the wide spacing. The choice of compatible intercrops has to do with the experience and/or cultural beliefs or traditional folklores rather than scientific approaches which are issues of concern in research.

Most traditional cropping systems practice multiple cropping to obtain early returns, serve as security against hazards and aid in weed suppression. Traditional multiple cropping systems characterized by minimal use of inputs such as fertilizers and pesticides, emphasizing the production of healthy, safe, and high quality food in the context of environmentally sound production (Lithourgidis *et al*., 2011), has been shown to produce higher and more stable yields in a wide range of crop combinations, and are estimated to provide as much as 15–20% of the world's food supply (Altieri, 1999). Due to declining land sizes and food security needs, the traditional multiple cropping systems have been engraved and commonly adopted in most farming systems in tropical Africa (Dakora, 1996). Apart from savings in the high cost incurred for major farm operations such as weeding, direct benefits obtained from intercropping include early income from harvests of annual vegetable and/or biennial intercrops before the main fruit crop is harvested (Aiyelaagbe and Jolaoso, 1992; Olubode *et al*., 2008). The reduced individual crop performances of component crops, notwithstanding, intercropping systems result in more overall yield because of more efficient utilization of environmental resources compared to mono-cropping (Aiyelaagbe and Jolaoso, 1992; Zhang and Li, 2003; Olaniyan *et al*., 2006; Magdy *et al*., 2007; Mousa *et al*., 2007; Olubode *et al*., 2008).

Figure 2. Intercropping cashew-plantain as an alternative to mono-cropping and better management of the biodiversity.

Intercropping has been extensively applied to cashew crops, particularly at the establishment phase, in line with an age-long practice of tree cultivation in the tropics (Opoku-Ameyaw *et al*., 2011). The utilization of mixed crops in cashew systems is very common among small and medium cashew producers (Cavalcanti, 2003). The performance of integrated systems depends on the choice of the food crop to be coupled with cashew. The use of early-bearing low-growing food intercrops are preferred, where significantly improved growth of cashew seedlings when associated with maize and groundnut was observed (Opoku-Ameyaw *et al*., 2011), unlike tall intercrops such as certain varieties of sorghum (*Sorghum bicolor* (L.) Moench) and millet that cast too much shade thus have a negative effect on cashew seedling growth (Ohler, 1979). However, while intercropping of cashew with citrus and coconut, or with cassava, groundnuts, and maize was more widespread in other areas, the cashew was also used as an intercrop in sheanut stands, and the association with sheanut stands was proven successful (Opoku-Ameyaw and Appiah, 2000). In the same vein, in other ecologies, tropical farmers in wetter regions combine cashew plantings with major commodity crops like cocoa, oil palm, rubber or kola while in the drier areas cereals and pulses are planted beneath the cashew orchards (Aliyu and Hammed, 2008).

Crop physiological and morphological responses are often altered in situations of higher planting densities or by the presence of another crop represented by mono-cropping or multi-cropping systems due to intra- and inter-specific competition (Vandermeer, 1990). Leaves of intercropped cashew contained more chlorophyll and carotenoids than leaves of monocrop plants, while in the latter leaf fresh/dry weight and nitrate reductase activity were higher, but no difference in stomatal frequency was observed between the monocrop and intercropped cashew (Balamisamy *et al*., 1993). Various ecological relationships in crop mixtures resulting in reduced crop yields have been associated with less water in the soil exploited by component crops, shading close to taller crops, phytotoxins in the soil, and competition for nitrate-nitrogen (May and Ash, 1990; Breener *et al*., 1993; Lisanework and Michelson, 1993; Onyewotu *et al*., 1994; Kowalchuk and de Jong, 1995). Nevertheless, profitable and yield-enhancing intercropping systems have to do with the compatibility of component crops in terms of favourable competition for soil nutrients, soil moisture, and light (Olubode, 2012).

Produce handling and storage techniques

The cashew production and fruit season is short but differences occur in the storage requirements and duration intervals for the cashew apple or nut products. Different postharvest losses have been estimated for different categories of crops, *viz*. overall average of 37% for plantain and 33% for vegetables (Hamilton, 2010; Olayemi *et al*., 2012); 13% for rice, 26% for cassava, 42% for tomato, and 50% for fruit and vegetables (OECD, 2013). The majority of technologies and best practices for reducing food loss and waste throughout the value chain fall into three categories: packaging, cold chain management, and promotion of 100% utilization of food (Kitinoja, 2016). Most producing farms go for the nut and allow the apple to waste. Although elsewhere processing industries are on the increase as cashew industry with support from foreign aid agencies, supported by domestic government policies, had networking relationship and render marketing assistance to both producers and growers which in return assisted the industry to increase production in response to demand (Gehrke *et al*., 2007), nevertheless in other areas more processing companies were closed down due to pressures from the immediate environment (Catarino *et al*., 2015). These include poor supplies due to cultural attitudes, competition with local buyers or middle men, poor governmental intervention, cost of power generation, and lack of financial back up and other managerial problems. Most tropical cashew producers export crude due to poor financial power, poor infrastructures and poor access to needed power generation.

Methods of maintaining shelf life of cashew apples under different treatments include that where cooling at 0–1.5 °C and relative humidity 85–90% maintained apples for 4–5 weeks; deep freezing maintained apples for 4–5 months; dipping with 0.25% citric acid and 500 ppm SO_2 maintained apples for 3 weeks (Wardowski *et al*., 1991; Jøker, 2003). Among the different treatments that included dipping in copper sulphate solution, bavistin (canbandazin), mustard oil, neem oil, GA3, NAA or potassium metabisulphate + sodium benzoate + citric acid, the lowest incidence of microbial decay and weight loss occurred in fruits with 1% mustard oil in which the storage limit was 6 days (Narayan and Ghosh, 1993). Deep freezing also reduces the astringency; and frozen apples can be used for apple pies or ice cream (Jøker, 2003). The optimum conditions for refrigerated storage was at 5 °C temperature and RH of about 85–90% that retained acidity, pH, TSS and ascorbic acid for storage up to 8 days (Rajan, 2016). However, compared with the high cost involved in developing cold storage or controlled atmosphere storage, the zero energy evaporative coolant structure (ECS), a humidity chamber not only reduces the storage temperature but also increases the relative humidity in storage, thereby provides basic essentials for maintaining the freshness of the commodities (Babarinsa and Nwangwa, 1986). The mean temperature and relative humidity in ECS storage structures was lower with 19–26 °C and 89.5%, respectively, than the ambient storage conditions of 28–31 °C and 61.14%, respectively, and had lower produce weight loss (5.95%) than in ambient conditions (18.39%) (Muhammad *et al*., 2011; Sunmonu and Jimoh, 2015).

In addition, ECS are beneficial and convenient for rural farmers because they are cheaper, accessible and can store harvested produce well for considerable periods (Odeyemi, 2013; Babatola and Olaniyi, 2007; Harris *et al*., 2010). The “wet-jute box” was also considered a more efficient method than “pot-in-pot” for produce preservation (Odetayo *et al*., 2013). However, for storage of various farm products, the ECS design using “metal-in-block” has been reported as the most efficient method, followed by “pot-in-pot” while “metal-in-pot” was the least efficient (Okunade and Ibrahim, 2011). There is therefore the availability of different low-cost locally manufactured storage devices although research into larger sizes with large storage capacities of similar effectiveness should be encouraged.

Grading, processing and marketing of cashew produce

As regards seasonal production, the harvest period in a growing region is quite short. However, because the nuts can easily be dried and stored for at least a year, the processing industry is not so sensitive to finding continuous supplies (Jaeger, 1999). The relevance of seasonality is mostly due to the anticipation of availability and therefore pricing of raw nuts. Seasonality in producing countries showed that production season in India, Vietnam and West Africa is March–June, Brazil is July–February while East Africa is October–December (Jaeger, 1999). Some farmers harvest the cashew apple before they drop to prevent pilferage and apple bursting. However, this practice very often results in poor quality of the kernels. High quality nuts are obtained when nuts are separated from freshly fallen cashew apples and sundried to bring down the moisture content from about 25.0 to 8.5% (Asogwa *et al*., 2008). The drying process helps to retain flavour and quality of the kernels. Nuts are usually gathered every week during the harvest season. When apples are for processing however, harvesting is usually done before they drop (Asogwa *et al*., 2008).

Harvesting is usually carried out manually from the ground, which is highly labour-intensive and involves women and children. The benefits from participating in the value chains of these products have increased for both men and women, hence women in cashew processing groups earn substantially higher income (Ingram *et al*., 2015), and revenue from the cashew harvest by the women represented more than half of their annual earnings (Lea *et al*., 1990; Catarino *et al*., 2015). Alternatively, it is done by using a small basket or sack attached to a ring at the end of a long stick (Azam-Ali and Judge, 2001). Currently, 75 to 80% of cashew nuts produced in Nigeria are exported, as very few companies are involved in local processing of the produce (May and Ash, 1990).

Grading of cashew nuts is determined by international quality standards such as those of the Association of Food Industries (AFI) in the US, and the Cashew Export Promotion Council of India (CEPC). The benchmark grade of over 30 different grades is “W320” as it is the most suitable for snack foods. On the international market, prices are quoted in dollar pound^{-1} (Cambodia Agribusiness Series, 2010). Whole kernels without defects or blemishes are required for the snack trade, while the broken pieces are required for other confectionery, biscuits and bakery products, and other prepared foods. The premium grades are the ‘wholes’, and these are divided into ‘white wholes’ and ‘scorched wholes’, depending on the color. Each class is then sold on a size count, ranging from 180 (*i.e.*, 180 kernels pound^{-1}), to 500 with “W320” as the benchmark grade (Jaeger, 1999). The broken kernels are also divided into whites and scorched, and then graded into ‘butts’, ‘splits’, ‘pieces’ and ‘baby bits’ and so on, depending on the size of the piece.

Figure 3. Small-scale roasting unit at farm level, enabling additional value and skipping storage losses.

Traditionally the various processing operations are performed manually or by using very simple mechanical driers, ovens and shelling machines, while the grading of kernels remain labour-intensive manual operations. The profitability of cashew processing depends largely on the proportion of whole, unblemished kernels after shelling. The cashew nut processor aims to crack the nut shell and remove it, before peeling away the testa, without scorching or breaking the kernel (Jaeger, 1999). The processor is thus confronted by three intrinsic difficulties; firstly, the nut has an irregular shape, secondly, there is a tough leathery shell which fits the brittle kernel closely, and thirdly, the shell contains a caustic phenolic liquid (CNSL) which is unpleasant to handle and must not be allowed to contaminate the kernel (Jaeger, 1999). For many years, mechanized or semi-mechanized shelling was a failure because it damaged up to 60% of the kernels, while hand shelling damaged only 15–20%. Because the highest prices are paid for whole, unblemished cashews, cashew shelling and grading have remained largely manual (Cambodia Agribusiness Series, 2010).

Although the critical processes are the roasting, shelling, drying, peeling and grading, the step-wise procedure for processing of cashew nuts involves: 1) Cleaning; 2) Calibration; 3) Humidifying – the nuts need to be brought to about 16% moisture level; 4) Roasting – this removes the CNSL and, depending on the process, may make the shell brittle and easier to crack; 5) Second cleaning and cooling to remove any remaining CNSL on the surface; 6) Second calibration, where the nuts are to be cut mechanically – they must be accurately graded before submission to the cutting process; 7) Shelling; 8) Separation, to remove remaining bits of shell; 9) Pre-grading, separates the wholes from the broken kernels; 10) Drying, for better storage and easier peeling of the testa which shrivels when dry; 11) Peeling, to remove the testa; 12) Grading to international specifications; 13) Re-humidifying to 5%, otherwise the kernels are too brittle; and 14) Packing. There are variations of all these steps and most can be mechanised with degrees of success (Jaeger, 1999).

Call for new production strategies

The various challenges facing cashew production as enumerated above call for the adoption of new production strategies to improve production, productivity and profitability. The low yield and hence low income encountered by the small farm holders that form the majority of the cashew producers calls for improved innovations in technological resource input, research into higher yielding varieties through plant breeding programmes, improvising new cultural practices to increase crop yield and enhancing extension workers adequately for dissemination of the new innovations. All these require government interventions to achieve set objectives as technologies are mostly power driven with the attendant exorbitant costs. It is opined that improved power generation will provide a synergy for the mechanized nut processing companies. In order for cashew production to be fully exploited, it is important for the government to incentivize care and maintenance of those already growing as well as young entrepreneurs to enter the sector (FAO, 2015). Earlier suggestions proposed that farmers need exposure to modern production techniques and direct government intervention by improving rural extension services to introduce fruit crop farmers to improved production techniques that will ensure high-grade produce for increased supply to local markets and for export (Olubode *et al*., 2016a). Fair and farmer-friendly policy will provide enabling environment for improved value chain which will result in an enhanced produce production and greater productivity among farmers, improved livelihood for the rural farmers and an increased gross domestic product in the nations.

Conclusion

Although efficiency of production may vary across different production areas due to varying soil types, climatic differences and available environmental moisture, optimising resource input to high efficiency level through knowledge-driven techniques could assist to boost yield production and productivity per unit area of land to hitherto unachievable levels which should be the goal of research. While research into high yielding dwarf varieties using plant breeding techniques may be a long-term but viable approach, nonetheless the use of cultural methods using population dynamics, dwarfing rootstocks, hormonal control mechanisms, and application of irrigation and fertilizer routines may be viable options. Adoption of suitable pruning methods and compatible intercrops to accommodate complementary cropping systems and facilitate adequate weed maintenance will improve productivity. The adoption of high efficiency 'low-tech' machines to reduce exposure to health risks of the work force (mostly women and children) in the production value chain, improved processing techniques with communal approach to solve the high energy cost from power-driven machines, reduction to minimal level of the use of manual approaches in most processing operations, and the adoption of zero-energy storage facilities will improve the efficiency of production. Most importantly, governmental support to resource-poor farmers through enacting farmer-friendly policy, better and more efficient extension programmes, farmers' development through capacity building, provision of adequate incentives to organic production methods, and lower production cost made available to high-intensive plantation-based production methods will boost production levels and improve the growers' income as well as advance their livelihood with accruable meaningful contribution of agricultural production to the economic growth and developments of producing countries.

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