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REVIEW ARTICLE

# Influence of environmental factors and production practices on the growth and productivity of pawpaw (*Carica papaya* L.) in south western Nigeria – A review

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**Abstract – Introduction.** Maximizing the production and productivity of pawpaw (*Carica papaya* L.) under rain-fed conditions requires a better understanding of the crop, which in turn will enhance its acceptability among fruit growers in the tropics. **Materials and methods.** This paper reviews the important limitations observed in the production practices, assesses the various factors that contribute to pawpaw productivity and evaluates the potential to optimize the crop development, its management and economic outputs. **Results and discussion.** The number of leaves and plant leaf area index are very responsive to growing conditions but more research is needed on the effect of canopy variation between cultivars. Studies on pawpaw root systems are few, especially the impact of different soil types on rooting volume, despite their essential role in the plant growth. As a long duration crop with replant problems, early inter-planting with annuals and crop rotation or inclusion with compatible crops are discussed. Successful inter-planting requires plant spacing suitable for the plant architecture of various cultivars as well as appropriate plant population and time of inter-planting with secondary crops. **Conclusion.** Optimizing pawpaw management can improve the economic performance of this underutilized crop and increase the benefits accruable from its adoption by fruit growers.

**Keywords:** Nigeria / papaya / *Carica papaya* / fruit production / cropping system / postharvest management / shelf life

**Résumé – Influence des facteurs environnementaux et des pratiques de production sur la croissance et la productivité de la papaye (*Carica papaya* L.) dans le sud-ouest du Nigeria – Revue de synthèse. Introduction.** Maximiser la production et la productivité du papayer (*Carica papaya* L.) en conditions pluviales nécessite une meilleure compréhension de la culture, ce qui permettra d'améliorer son acceptabilité par les producteurs de fruits sous les tropiques. **Matériels et méthodes.** Cet article examine les contraintes majeures observées dans les pratiques de production, évalue les différents facteurs qui contribuent à la productivité du papayer et évalue le potentiel d'optimisation du développement, de gestion et de production économique de cette culture. **Résultats et discussion.** Le nombre de feuilles et l'indice de surface foliaire de la plante sont des paramètres très sensibles aux conditions de croissance, encore qu'il reste nécessaire d'étudier l'effet de la variation du volume de feuillage entre cultivars. Les études sur le système racinaire du papayer sont peu nombreuses, en particulier l'étude de l'impact des différents types de sol sur le volume de l'enracinement, en dépit de son rôle dans la croissance des plantes. En tant que culture de longue durée posant des problèmes de replantation, les principes d'une culture annuelle précoce associée, des cultures compatibles en rotation ou en inclusion sont discutés. Une plantation réussie en culture associée nécessite une densité de plants adaptée à l'architecture des plantes selon le cultivar, ainsi qu'une densité de peuplement végétal appropriée et une programmation dans le temps des cultures secondaires intercalaires. **Conclusion.** Optimiser la gestion du papayer permet d'améliorer la performance économique de cette production végétale sous-utilisée et d'augmenter les avantages potentiels de son adoption par les arboriculteurs fruitiers.

**Mots clés :** Nigéria / papayer / *Carica papaya* / production fruitière / système de culture / gestion post-récolte / aptitude à la conservation

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## 1 Introduction

Pawpaw (*Carica papaya* L.) is a native of tropical America from where it was spread throughout the tropical world [1]. As an important agricultural export for developing countries, the export revenues of the fruit provide a livelihood for thousands of people, and contribute to the growing supply of healthy food products in international markets [2]. The nutritional importance of fruit crops has been well documented [3–8]. The appropriate intake of essential vitamins and mineral elements contained in the fruit is emphasized as important for the maintenance of human health [9, 10]. Among the fruit crops that supply health-supporting nutritional daily intake is pawpaw [11]. It is reported that consumption of 90 g and 135 g of pawpaw everyday will meet the dietary allowances of vitamin A recommended by the USDA for children and adults, respectively [12]. Pawpaw has a good amount of minerals and carotene; it is regarded as a good source of iron, calcium, vitamins A, B and C. Nonetheless, its carotenoid content is low compared with mango and tomato [6]. Pawpaw is also valued for its medicinal properties [13]. Various studies have established the potential use of both latex and its components as valuable sources of medicinal products that can be used for treatment of life threatening infectious diseases [14].

The world pawpaw production was estimated in 2010 [15] at 11,223,031 metric tons (t), including 4,713,800 t from India (38.61%), 1,871,300 t from Brazil (17.50%), 703,800 t from Nigeria (6.79%), Indonesia (695,214 t), Mexico (616, 215 t) and Ethiopia (232,400 t). In 2010 the production was 7.26% higher than in 2009, and 34.82% higher than in 2002 [2, 15]. Asia has been the leading pawpaw producing region, accounting for 52.55% of the global production between 2008 and 2010, followed by South America (23.09%) and Africa (13.16%) [2, 15, 16]. The biggest increase in global pawpaw production occurred between 2009 and 2010, as production in India increased by 20.50% following a combination of increased planted area, improved genetics, and better management. The total exports in 2009 were estimated at 268,476 t, a 31.5% rise over the weight exported in 2002, with an estimated value of about $197.2 million [2]. Other countries involved in commercial pawpaw production for papain include Sri Lanka and Tanzania.

Production of fresh fruit per hectare differs among cultivars. The choice of cultivar to grow depends on the required production type or use to which the fruits is to be put [17]. For local fresh fruit consumption or supplies to distant market indices such as fruit quality, flesh color, taste and firmness, and consumer preference count. Generally, the dioecious pawpaw cultivars are preferred for extraction of papain because the yields and proteolytic activity of the crude papain from the female fruits are greater than those of the hermaphrodites [18]. However, for commercial fruit planting, hermaphrodite plants from Solo group of pawpaw are preferred because they produce pear-shaped fruits which have thicker flesh and smaller internal cavity than fruits from female plants [19].

The industrial importance of pawpaw lies in its production of papain and other related proteolytic enzymes such as chymo-papain. Papain, a thiol protease which is abundant in the milky latex of fruits, is used for food and for the textile and perfume industries [20, 21]. Papain is collected by making incisions in unripe pawpaw plants. Although fruits weighing 0.5 to 1.0 kg contain larger amounts of latex, fruits that weigh 1 to 2 kg ripen while those between 200 and 300 g stop developing after latex extraction [22]. The papain extracted from fruit ranges between 4 and 6 g fruit$^{-1}$ equivalent to 250–300 kg ha$^{-1}$ [23]. The latex, a sticky emulsion that exudes upon damage from specialized canals occurs in about 10% of flowering plant species, tends to be more phytochemically diverse than resins, mucilages, and gums, and often contains complex mixtures of terpenoids, phenolics, proteins, and alkaloids [24, 25]. Latex fractions from ten latex producing fruit species: *Spondias dulcis* (ambarella, "amra" in Tamil), *Diospyros melanoxylon* (East Indian ebony, "tendu" in Hindi), *Terminalia bellirica* (Belleric, "bahera" in Marathi ), *Ficus glomerata* (Indian fig tree or gular), *Phyllanthus emblica* (emblic or myrobalan, "awla" in Marathi), *Thevetia neriifolia* (yellow oleander or lucky nut in the West Indies), *Carica papaya* ("papita" in Hindi), *Calotropis procera* (kapok tree or Sodom apple), *Ficus benghalensis* (Indian banyan, "baut" in Bengali), and *Artocarpus heterophyllus* (jakfruit, "kathal" in Bengali), evaluated for their potency against microbial infections, registered significantly higher growth inhibition than that of broad spectrum antimicrobial drugs [26]. Dried pawpaw latex contained higher amounts of crude protein (57.24 ± 0.69%), followed by moisture (17.76 ± 0.09%), ash (7.00 ± 0.01%), crude fat (5.21 ± 0.13%) and crude fibre (0.67 ± 0.09%). In the enzyme analysis, papain had protease activity of 2,655 units g$^{-1}$ at pH 5.5 and 285 units g$^{-1}$ at pH 9.0 [27]. With an estimation of 515.6 USD profits obtainable per hectare per year, production of papain latex is an economically important alternate product of pawpaw. Nonetheless, pawpaw cultivars differ in papain yield depending on fruit shape, stage of maturity, season of tapping, tapping time of the day, pattern of tapping, and frequency of tapping [28, 29]. The repeated use of ethephon applications in coconut oil at 37mM has been shown to increase papain yield [30] as cited by [28, 29]. Among the tested varieties, 'CO-6' was found better for fresh weight as well as dry weight of latex as well as fresh and dry yield of papain in 80 days old fruit [31].

In the production of rain-fed crops in the semi-arid tropics, large variations in crops occur in response to the fluctuations in seasonal rainfall. Hence, in dealing with the variability of rainfall both within and between seasons, it is critical to identify strategies that can sustain high levels of production for rain-fed regions [32]. Considerable uncertainty still exists on how crop species will respond to the observed alterations in global temperature and precipitation patterns [33–35] which pose significant threats to their existence and productivity. Improvement of crop yields in the tropical environment where low yields and low quality confront growers will require manipulation of important growth factors such as supplemental irrigation, plant/soil nutrition, and light and temperature, and this should be an important aim of research [36]. Although Chovatia *et al.* [31] reported no significant difference among varieties for number of fruits per plant and fruit yield, Olubode *et al.* [37] reported that the 'Homestead selection' variety had significantly fewer fruits but greater fruit yield than 'Sunrise Solo'.

Fleshy and hollow berry fruit varies in size from moderate to large. Fruits formed from female flowers are oblong to nearly spherical but those formed from bisexual flowers are pear-shaped, cylindrical or grooved. Marketable fruits weigh from 0.5 to 2.0 kg [3] and are 10 to 20 cm long. The thin green skin turns yellow at the bottom when maturity sets in. The flesh is yellow to orange, in some cultivars reddish, and has a pleasant flavour. Around the cavity lie a thousand or more black seeds, but seedless fruit also occur. Twenty air-dried seeds weigh about 1 g [38].

Pawpaw has a tremendous yield potential due to its precocious bearing and indeterminate growth habit with simultaneous vegetative growth, flowering and fruiting [39]. The short-lived, near herbaceous, soft woody perennial fruit crop has trees that bear early and supply fruits continuously throughout the year. As a trade commodity with world-wide production, adequate knowledge of pawpaw responses to soil moisture regimes either in monoculture or polyculture, various intercropping systems, and the application of conventional and/or organic farming practices for improved farm management practices will enable growers to manipulate the crop for higher productivity. Although production, especially in tropical Africa including Nigeria, has hitherto been limited to volunteer crops located in home gardens or scattered in open fields [17], recently there has been the planting of medium to large scale pawpaw orchards. These produce large consignments of fruit destined for urban centres such as Lagos and Port Harcourt in the south of Nigeria, and Abuja and Kaduna in the North. Some of the fruit also contribute to Nigeria's foreign exchange [40, 41].

In their critical review of research findings from experiments on indicators and methods using intercropping, Connolly *et al.* [42] observed that two-thirds of the experiments were carried out on research station, only 10% on farm and 24% in undefined location, about half of which were with annual species only and only about one third involved at least one perennial species including banana (*Musa* spp.) as a fruit crop. This review confirms the paucity of information on intercropping systems involving perennial crops such as pawpaw.

Many problems confront pawpaw growers, among which are the unpredictability of environmental conditions, aggravated by climate change, leading to significant adverse effects on growth and yield, and to dwindling revenues. There is the possibility that deploying interventions such as intercropping with compatible annual crops, with timed introduction of selected intercrops at appropriate population levels could lead to effective and efficient use of resources to maximize component crops production and cropping system productivity. This article identifies aspects of pawpaw based cropping systems that require further research.

## 2 Vegetative growth

### 2.1 Modern propagation methods

Although true-to-type pawpaw plants that bear earlier, lower and longer can be obtained through vegetative means by grafting and cutting [43] cited in [41], economic considerations indicate that pawpaw is better propagated from seeds which abound in the fruits. Moreover, intensive propagation of clonal material can be achieved through tissue culture, although this is rarely practised because most people engaged in pawpaw cultivation are resource-poor. Pawpaw is therefore commercially propagated by seed [44]. Being open pollinated, cross pollination often results in a loss of varietal purity [45]. Genetics × Environment interactions also often produce a wide array of modified forms, so also the number and types of modifications [4]. Consequently, special breeding programmes and experimental designs are needed to distinguish genotypic from phenotypic variation in pawpaw [46].

The irregular and slow germination due to the physiological quality of pawpaw seeds constitutes an obstacle to pawpaw propagation Among the problems observed are the influence of harvest season on seed quality [47]; postharvest storage of fruit [48] the presence of sarcotesta [47], and the presence of inhibitory compounds in the seed structures [49]. 'Sunrise Solo' pawpaw seeds that had lower density seeds were observed to have abnormal embryos [50]. High physiological quality seed was obtained from the central portion of fruits at the fifth (75% maturation) and final maturation (100% maturation) stages [51], and postharvest maturity of fruit which improved the physiological quality of pawpaw seeds caused a reduction in dormant and non-viable seeds However, an X-ray test proved to be adequate in evaluating the morphological quality of pawpaw seed, thus distinguishing between empty seeds and seeds with normal embryos [51].

### 2.2 Germination and seedling growth rates

Temperature is one of the best indicators among the climatic factors that determine the establishment of pawpaw; hence, pawpaw trees grow faster in warmer regions, and the fruit is of better quality than that in cooler regions [52–54]. Moreover, temperature is an important factor that controls changes in crop development from germination and emergence through vegetative growth to floral initiation and reproductive growth [55]. Hence in regions where temperatures drop below 15 °C, the growth of pawpaw trees is curtailed; thus, no flowering occurs, fruit maturation is delayed, and most leaves are shed, which causes sunburn of exposed fruit [56, 57]. Furthermore, every phase of a fruit crop is moisture sensitive, although the degree of moisture sensitivity differs [8]. Thus a perennial nature, with part of the life cycle spanning the dry season under rain-fed condition, exposes the crop to soil moisture stress with widely reported deleterious effects on growth, development and yield [41, 58–60].

The critical water potentials for pawpaw seed germination, seedling growth, vegetative growth, flowering, fruiting phase, flowering through fruiting were reported to be –0.01, –0.02, –0.02, –0.20, –0.20, –0.02 MPa, respectively [41]. Allowing soil moisture to deplete cyclically below –0.02 MPa soil water potential by watering once in 11 days retarded growth of 'Homestead selection' pawpaw seedlings in the nursery and delayed attainment of transplantable size [61], while drought imposed by withholding irrigation at the fruit set stage decreased leaf area, total dry matter accumulation, fruit set and fruit weight of field grown 'Homestead selection' pawpaw [62]. Although a moisture level that is adequate for germination of some seeds may be either insufficient or excessive for others; thus, withholding water for 6–9 days before watering delayed and decreased germination of 'Homestead selection' pawpaw seeds compared with those watered daily, but enhanced the germination of 'Allahabad Safela' guava (*Psidium guajava* L.) [41,63]. The reports by Aiyelaagbe *et al.* [64] and Rice *et al.* [65] indicated that marked reductions in water availability in soils tended to limit bud initiation in many fruits, including pawpaw, where both leaf and flower drops were recorded under pronounced moisture stress.

## 2.3 Plant architecture and root plasticity

Crop communities show a sigmoid pattern of growth during the growing season. In the early lag phase; growth of new seedling is proportional to the leaf area index of crops. As plants increase in size they overlap to an increasing extent in both the aerial and soil environments where adjacent plants begin to interfere (compete) with each other for the limiting resources of light, water, nutrients and $CO_2$. As a result, growth rates and morphologies of individual plant change drastically with density, and each plant produces less than it would with unlimited space but production from the community is optimized. Thus the smallest plants with least resources become further disadvantaged and die, leading to self-thinning in crowded communities. The open space now allows for expanded growth of neighbors as explained by Kira plot of 3/2 replacement theory ([66] as cited in [67, 68]).

Morpho-plasticity is the capacity of plant roots to modify their morphology in response to the soil environment [69]. Morpho-plasticity includes situations where crop architecture changes result from crop adjustment to increasing density, along with etiolation, both of which occur when crop densities, either of monoculture or polyculture (cropping mixtures), deny crops limited resources. Crop architecture returns to normal when optimum spacing and resources are available. Pawpaw roots are highly morpho-plastic and pawpaw plants grown on hillsides with 70% slope were able to produce ascending root growth provided that the soil conditions were favourable for root growth [70].

In a study with three morphotypes, sourced from each of two cultivars of pawpaw, 'Homestead selection' and 'Sunrise Solo', morphotypes from 'Homestead selection' were taller and wider, and had more numerous leaves and longer petiole, while the morphotypes from 'Sunrise Solo' had thicker girth and wider leaf angulation [71]. Thus cultivars possess distinct but different plant architecture that changes with time and with crop requirement in response to environmental conditions (*figures 1–4*). Despite this, few recommendations are available for spacing under monoculture conditions and cultivation of pawpaw in multiple cropping systems adds complexity that could possibly have a significant effect on production and productivity. Thus appropriate knowledge on pawpaw morphology is a prerequisite for devising optimum plant spacing or spatial arrangement in crop mixtures for maximum productivity of the cultivars under field conditions.

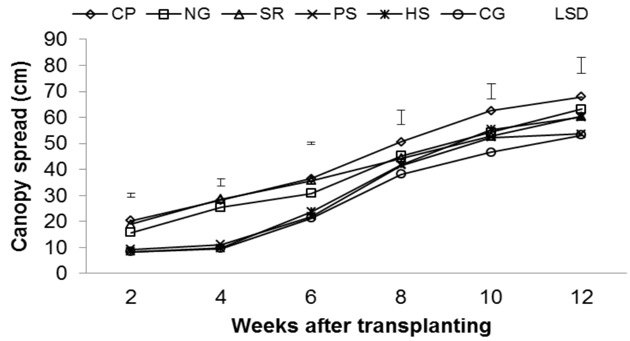


**Figure 1.** Canopy spread obtained for pawpaw cultivars at early seedlings stage. CP, NG and HS are code names for 'Homestead selection' morphotypes; SR, PS and CG are code names for 'Sunrise Solo' morphotypes. Source: Olubode *et al.* [71].

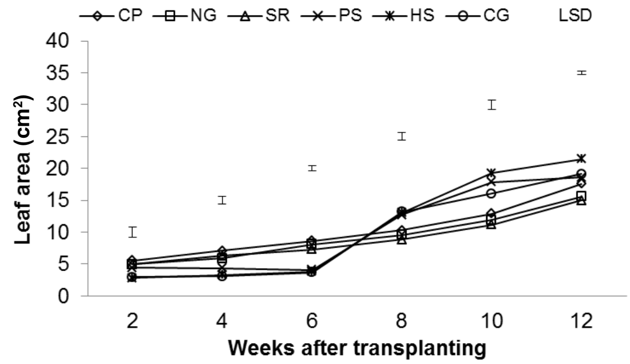


**Figure 2.** Leaf area ($cm^2$) obtained for pawpaw cultivars at early seedlings stage. CP, NG and HS are code names for 'Homestead selection' morphotypes; SR, PS and CG are code names for 'Sunrise Solo' morphotypes. Source: Olubode *et al.* [71].

## 2.4 Fertilizer use in crop productivity

### 2.4.1 Nutrient-use efficiency

In fertilizer trials, the crop yield obtained without added fertilizer reveals the amount of nutrient supplied by soil [67]. The apparent fertilizer use efficiency is measured by the slope of the yield response to added fertilizer, thus efficiency is large when the nutrient is highly deficient, giving rise to a sharp transition between deficiency and adequate supply. In the same way nutrient–use efficiency (NUE) is defined by the biomass yield curve obtained when plotted as a function of nutrient uptake, expressed, for example for nitrogen fertilizer as kg dry matter yield $kg^{-1}$ N. This relationship follows a diminishing return but stops short of a plateau. Biomass yield curves can indicate the maximum and minimum above ground biomass that the crop can produce per kg nutrient taken up.

The rapid growth, continuous fruiting and heavy yield of pawpaw characterize it as high nutrient exhaustive fruit crop. Thus, for high productivity expected nutrient removal at the time of harvest was estimated at about 310, 105, 530, 3332 and 185 kg $ha^{-1}$ of N, P, K, Ca and Mg, respectively [72]. This necessitates judicious application of fertilizers to meet

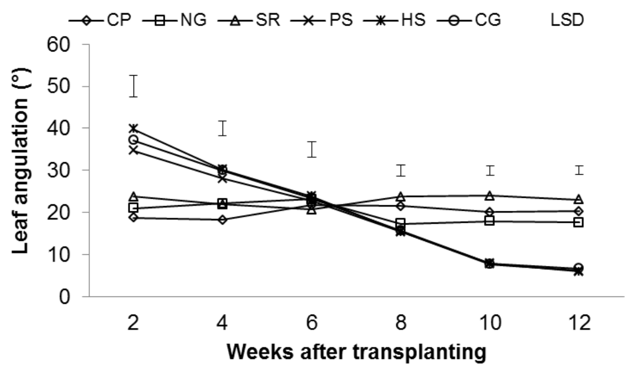


**Figure 3.** Leaf angulation obtained for pawpaw cultivars at early seedlings stage. CP, NG and HS are code names for 'Homestead selection' morphotypes; SR, PS and CG are code names for 'Sunrise Solo' morphotypes. Source: Olubode *et al.* [71].

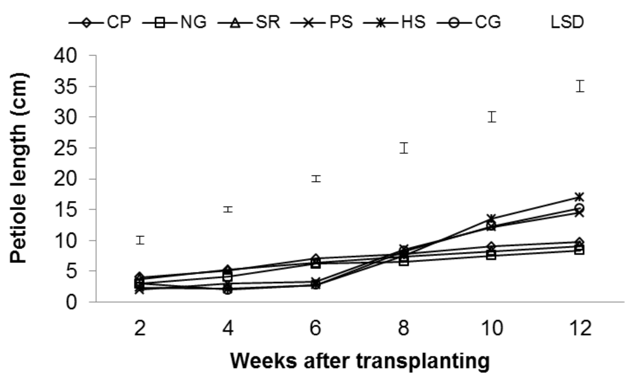


**Figure 4.** Petiole length obtained for pawpaw cultivars at early seedlings stage. CP, NG and HS are code names for 'Homestead selection' morphotypes; SR, PS and CG are code names for 'Sunrise Solo' morphotypes. Source: Olubode *et al.* [71].

the nutritional requirement of the plants [73]. Fertilizer recommendations for optimum pawpaw fruit yield for locally available varieties such as small sized 'Sunrise Solo', moderate sized 'Homestead selection' and large sized 'Dahomey Large' in south west Nigeria include 50 g tree$^{-1}$ month$^{-1}$ of NPK (15-15-15) [74], and the application of 250 g N plant$^{-1}$ and 150 g $P_2O_5$ plant$^{-1}$ which produced yields of 38.21 and 39.51 kg plant$^{-1}$, respectively, in 'Sunrise Solo' [75]. Pawpaw fruit yield, petiole N content and water use efficiency were higher with 450 g than with 150 g N plant$^{-1}$ in cv. Coorg Honey Dew [76]. In order to improve yield and quality of fruit, depending on choice of cultivar, farm location and the initial fertility status of the soil, the N requirement will vary from 140 to 375 g plant$^{-1}$, P from 70 to 340 g plant$^{-1}$ and K from 140 to 600 g plant$^{-1}$ [77].

### 2.4.2 Inorganic fertilizer in crop production

Soil qualities known to directly and indirectly affect the nutritional quality of crops include pH, available nutrients, texture, organic matter content and soil water relationships [78]. A balanced nutrient supply is therefore necessary not only for obtaining higher and regular yields of better quality fruits but also for increasing shelf life [39, 79]. The world total fertilizer production capacity was estimated as 278 Mt in 2013 with a total supply of 237 Mt and demand of 183 Mt [80], indicating that fertilizer production should be adequate for crop production. According to Adedokun and Aiyelaagbe [81], although chemical fertilizers provide readily available nutrients for plants, their use in tropical agriculture is nonetheless hampered by problems of high cost, scarcity and lack of established soil testing programmes, while their application increases soil acidity. Also, NISER [82] confirmed that farmers have limited access to inorganic fertilizers because of restricted availability, procurement and distribution, thereby necessitating the need for alternative means of maintaining soil fertility to support the high yielding crop varieties required to feed the ever- increasing human population.

### 2.4.3 Organic fertilizer in crop production

Organic agriculture includes agricultural practices that utilize natural (non-synthetic) nutrient-cycling processes to sustain or regenerate soil quality, such as the use of cover crops, manures, compost, crop rotation and intercropping [83]. Most organic farms therefore rely on the sustainable intensification of farm management practices that rely on renewable resources, ecological stability, and biodiversity [84] to increase productivity and lessen environmental degradation [85–87]. The application of organic manures sustains cropping systems through better nutrient recycling and improvement of soil physical, chemical and biological properties. Many waste and by-products, including municipal waste, possess considerable nutrient value and can be used as organic manure. These are often abundant in cities where they may become pollutants especially to water environment if not properly recycled [88]. Due to the bulky nature of organic manure, their field application may incur high transportation and labor costs. However, these materials are regarded as a safer source of nutrients than conventional fertilizers as they are environment friendly materials that through the activation of soil microbial activities release nutrients slowly in synchrony with the crop demand [89]. Organic manures provide long-term benefits to the soil structure and water holding capacity, and are cost effective and safe [90–92]. Olubode and Fawusi [93] observed the positive effect of organic manure on pawpaw growth and yield. For example, the application of poultry manure at an optimum application rate of 20 t ha$^{-1}$ significantly increased pawpaw growth and fruit yields in an organic production system [37, 93].

Despite the numerous benefits of organic manure application, critics have argued that there are insufficient organically acceptable fertilizers to produce enough organic food without substantially increasing the land area devoted to agriculture [82, 94, 95]. Also organic crop production is still lacking in terms of yield security and production costs are high compared with conventional and integrated fruit production [96]. However, when practised over a long period, the direct and indirect beneficial effects of organic management could contribute to a higher crop yield on a sustainable basis than is obtainable under less sustainable conventional farming. Although, nutrient supply from organic manure is strongly influenced by prevailing environmental conditions of temperature and water availability and N mineralization will be greatest during warmer periods when soils are moist [97–100]. Differences in the rate of release of nutrients from different fertilizers could therefore lead to different C/N ratios in plants and this in turn could lead to difference in the production of secondary metabolites [101]. Depending on the growers' primary objective, the quantity and quality of resource inputs can be manipulated to obtain maximum crop growth, productivity and crop quality.

Pawpaw responds well to fertilization; however the 'Homestead selection' and 'Sunrise Solo' pawpaw varieties did not differ in their nutritional requirements. The optimum yield could be obtained with 10 t $ha^{-1}$ of a fortified "Type A" organo-mineral fertilizer (OMF) [102] while an earlier report found poultry manure at 20 t $ha^{-1}$ to be the optimum application [37]. Also, the positive effect of OMF on post cropping soil fertility status was observed whereby soil acidity levels were moderated and decreased by the increased Ca and Na addition to the soil [102]. However, the lack of a significant effect of OMF on the post cropping levels of soil nitrogen and phosphorus suggested the relative inadequacy of OMF in supplying these nutrients to pawpaw. This in turn may suggest that the better performance of pawpaw with OMF than with inorganic NPK fertilizer was due to the supply of nutrients which were not present in the NPK (*table I*) [102].

## 3 Reproductive growth

### 3.1 Correlation among growth and yield parameters

The relationships among growth parameters, and between growth parameters and yield have been well documented. Babu *et al.* [103] observed a significant positive correlation between leaf area and petiole length in the cultivar $CO_3$ and from petiole length obtained a regression equation for determining leaf area under field condition. Aiyelaagbe and Fawusi [104] obtained a leaf area formula using regression analysis on mid-rib length. Reddy *et al.* [105] found a highly significant correlation between the petiole P concentration and yield; the relationship was strongest with recently matured leaves. Balakrishan *et al.* [106] obtained a highly significant positive correlation between dry weight and the product of tree height and stem girth in 10 cultivars of pawpaw. Ghanta *et al.* [107], in an experiment using levels of NPK on pawpaw cv. Ranchi obtained a positive and significant correlation between plant height and girth at flowering and yield per plant.

Using the $6^{th}$ leaf as an index leaf for plant nutrient analysis, Sanyel *et al.* [108] observed that the concentrations of all elements were generally higher in the leaf blade except for K which was higher in the petiole. The leaf blade tissue was the most useful for determining the P, Ca and Mg status of the plant while the petiole was best for K, and the optimum sampling time was at flowering. However, both leaf and petiole were suitable for analysing N status and the optimum sampling time was 3 months after flowering.

In crop mixture with pawpaw, 'Homestead selection' in monoculture showed a correlation between height and girth alone, but 'Sunrise Solo' in monoculture and 'Sunrise Solo' mixed with either okra or cucumber vegetable showed correlations among all parameters. The no correlation among parameters measured for 'Homestead selection' in cropping mixtures indicated the effect of competition among intercrops and that of component crops adaptability to vagaries of weather [37]. The results obtained confirmed those previously reported [103, 105–107] that mathematical relationships occur among pawpaw growth parameters which can be of significant use in growth modelling and productivity predictions. The reproductive parameter, weekly number of flowers, was negatively correlated with other parameters which shows that as these others increase flowers were either not produced or shed which is normal since flowers fall when not pollinated. The percentage contribution indicated by the regression analysis showed that greatest contribution to productivity prediction was through plant height (12.6%), girth (11.8%) and number of fruits (22.9%) for 'Homestead selection' and plant girth (49.5%), number of fruits (13.7%) and petiole length (10.4%) for 'Sunrise Solo' [37]. The main contributing factors to productivity therefore were number of fruits and plant height for 'Homestead selection' and girth, number of fruits and petiole length for 'Sunrise Solo' (*table II*) [37]. Olubode *et al.* [71] obtained taller plants with longer petioles in 'Homestead selection' pawpaw but thicker girth and wider leaf angulation in 'Sunrise Solo' which confirms differences in tree architecture displayed among varieties in the bid to catch sunlight, build assimilates and enhanced productivity.

### 3.2 Flowering and fruiting patterns

Flower initiation plays an important role in pawpaw plant development. The initiation of the flower primordial which signals the beginning of the reproductive phase, and the duration between planting the seeds and the first ripe fruit both vary with variety and climate. Aiyelaagbe *et al.* [64] reported that for 'Homestead selection' variety, flowering commenced 3 weeks after transplanting of 3 months old seedlings which reached maturity about 10 weeks later. Fruit setting rate has a direct relationship with the number of fruit set per plant and marketable fruit yield [109]. The expected yield is 28 t $ha^{-1}$ $year^{-1}$ at 15–20 fruits $tree^{-1}$ [110], with a yield potential of 50 t $ha^{-1}$ $year^{-1}$ [3], although a range of 30-50 t $ha^{-1}$ [111] may occur due to differences in management practices; and, while the average life span is estimated to be 25 years [112] only 5 years are considered economic.

As observed with many dioecious species, where male trees often exceed females in total plant size, plant height, growth rates, and frequencies in populations [113–115], taller female trees have been reported for 'Homestead selection' whereas significant differences between the sexes was not observed in 'Sunrise Solo' [116]. In general, for most plant species, more female than male flowers are developed under favourable conditions, while more male than female flowers are developed under stressful conditions [117–119]. However, among angiosperms, labile sex appears to be more common among dioecious and monoecious plants than among

**Table I.** Post cropping soil physical and chemical properties of pawpaw orchards in response to crop mixture with cucumber and applied organo-mineral fertilizer (OMF) application rates (O.M.: organic matter). Source: Olubode *et al.* [102].

| Treatments | Soil physical properties | | | Soil chemical properties | | Macronutrients | | | Micronutrients$^y$ | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | % Sand | % Clay | % Silt | pH ($H_2O$) | % O.M. | % N | $P^x$ | $K^y$ | Na | Ca | Mg |
| Crop varieties | | | | | | | | | | | |
| 'Homestead' | 78.6 | 14.7 | 6.6 | 4.7 | 4.7 | 0.10 | 2.53 | 9.3 | 4.5 | 0.86 | 0.68 |
| 'Sunrise' | 79.3 | 15.0 | 5.7 | 5.0 | 5.3 | 0.10 | 2.73 | 10.2 | 4.2 | 0.84 | 0.66 |
| *LSD var* | *ns* | *ns* | *0.1* | *0.05* | *0.02* | *ns* | *ns* | *ns* | *ns* | *ns* | *ns* |
| Crop Mixtures | | | | | | | | | | | |
| Sole pawpaw | 78.4 | 14.9 | 6.7 | 4.7 | 4.5 | 0.12 | 2.37 | 10.2 | 4.4 | 0.81 | 0.67 |
| Pawpaw in mixture | 79.5 | 14.9 | 5.5 | 5.1 | 5.4 | 0.07 | 2.88 | 9.3 | 4.3 | 0.89 | 0.67 |
| *LSD cmix* | *ns* | *ns* | *0.3* | *0.05* | *0.2* | *ns* | *ns* | *0.3* | *0.06* | *ns* | *ns* |
| Manure Rates | | | | | | | | | | | |
| 0 t $ha^{-1}$ OMF | 80.3 | 15.0 | 4.5 | 5.1 | 4.7 | 0.07 | 1.53 | 7.0 | 4.2 | 0.79 | 0.64 |
| 10 t $ha^{-1}$ OMF | 80.2 | 13.9 | 5.9 | 4.8 | 4.7 | 0.13 | 2.69 | 9.8 | 4.7 | 0.83 | 0.66 |
| 20 t $ha^{-1}$ OMF | 76.9 | 15.1 | 7.9 | 5.0 | 6.0 | 0.13 | 3.07 | 11.9 | 4.4 | 0.88 | 0.69 |
| 40 t $ha^{-1}$ OMF | 77.6 | 15.6 | 6.8 | 4.7 | 5.5 | 0.08 | 3.86 | 12.8 | 5.3 | 0.92 | 0.70 |
| NPK 15:15:15 | 79.6 | 14.8 | 5.6 | 4.7 | 3.9 | 0.07 | 1.99 | 7.3 | 3.2 | 0.83 | 0.67 |
| *LSD fert* | *0.7* | *ns* | *0.5* | *0.09* | *0.2* | *ns* | *0.2* | *0.7* | *0.2* | *0.03* | *ns* |
| Interactions | | | | | | | | | | | |
| var x cmix | * | ns | ** | ns | ** | ns | ns | ns | ** | ns | ns |
| var x fert | ns | ns | ns | ns | ** | ns | ** | ns | ns | ns | * |
| cmix x fert | * | ns | * | ns | * | ns | ns | ns | ** | * | ** |
| var x cmix x fert | ns | ns | ** | ns | ** | ns | * | ns | ** | ** | ns |

$^x$ in ppm; $^y$ in cmol $kg^{-1}$.
* = significant at $P < 0.01$, ** = significant at $P < 0.05$, ns = not significant; var = variety, fert = fertilizer, cmix = crop mixture.

**Table II.** Regression analysis showing the contribution effect of growth and yield parameters to productivity of two accessions of papaya (B = slope, SE = standard error). Source: Olubode *et al.* [37].

| Parameters | 'Homestead selection' | | 'Sunrise Solo' | |
|---|---|---|---|---|
| | B | SE | B | SE |
| Constant | 1.893 | 1.164 | 0.947 | 0.735 |
| Girth | 0.118 | 0.384 | 0.495 | 0.265 |
| Nfruit | 0.229 | –1.354 | 0.137 | 0.018 |
| Nleaves | –0.747 | –0.710 | –0.309 | 0.084 |
| Leaf area | $2.928 \times 10^{-4}$ | 0.028 | $7.291 \times 10^{-5}$ | 0.000 |
| Plength | –0.148 | 0.124 | 0.104 | 0.018 |
| NFlower | –0.028 | 0.000 | –0.141 | 0.035 |
| PHeight | 0.126 | 0.016 | $2.819 \times 10^{-2}$ | 0.013 |
| Crop produce | –30.88 | 0.016 | 0.038 | 0.220 |

hermaphrodites in which environmental stress, caused by less than optimal light, nutrition, weather or water conditions often favours maleness [120]. As sex expression is regulated by plant hormones, it therefore appears that the sexual expression is controlled by a balance between male promoting and female promoting hormones [121]. Gibberellins are usually associated with male flowers, while auxins, cytokinins, and ethylene are usually associated with female flowers [117,121]. Nonetheless, pawpaw exhibits wide morphological and biological diversity of its types with prominent sex specific characters, hence the plants can be either dioecious, monoecious or gynodioecious [122].

### 3.3 Factors limiting yield – agronomy, sex identification

Crop productivity is constrained by limiting factors including light, water and nutrient. Blackman ([123] cited in [124]) stated that plants respond proportionally to increased outputs of only the most limiting factor until another factor becomes limiting. Von Caemmerer and Farquhar [125] reported that photosynthetic assimilation of $CO_2$ by plants is often limited at the same time by several plant and environmental factors, and increasing the supplies of any of these factors increases the growth rate. Inclusive among these factors is the reluctance of farmers to adopt research results, as reported by Aiyelaagbe [126] from interviewed farmers who did not adopt the recommended practices for fruit growing. Other limiting factors include difficulty in obtaining seeds of improved varieties, the problem of excessive cross pollination, poor seed germination, and difficulty in sex identification of seedling age pawpaw at planting time.

Morphology-based sex identification during the seedling or early growth stage is virtually impossible due to a lack of clearly defined morphological features [127]. Male flowers do not produce fruit, and fruit developed from female flowers contains less flesh and more seeds than those from hermaphrodites indicating that female plants have less commercial value for the production of fruit and seeds [128]. To overcome this problem, conventionally, farmers grow two or three plants at stake which are later thinned to one upon flowering to maintain the male to female ratio of 1: 10 in the field for dioecious plants. For hermaphrodite pawpaw, to ensure profitable cultivation, it is necessary to grow more hermaphroditic plants than either male or female plants. Sex is one of the most important factors and traits for plant breeding and production [129]. Attempts made by Ajiboye [116] and Olubode [130] have not found convincing linkage between sex and morphological character. However, advances in plant breeding using specific genes or markers have been able to identify sex at the seedling stage [131]. Several male-hermaphrodite specific markers were independently developed by RAPD or AFLP, which were then converted into scar markers, *e.g.*, T12 and W11 [132], napf [128], and PSDM [133], to distinguish hermaphrodite from female pawpaw seedlings. These markers have been successfully applied to pawpaw production [127, 134, 135]. Despite the PCR-based sex-diagnostic methods being widely used, they require modern and expensive laboratory facilities and equipment, and might be difficult to perform, depending on the test location, particularly for field-based genotyping [136].

### 3.4 Yield improvements in organic farming practices

The influence of organic matter on soil biological and physical properties is well documented as it affects crop growth and yields, either directly by supplying nutrients or indirectly by modifying soil physical properties [137, 138], improves soil structures and water retentive capacity [139], increases infiltration rates [140] and decreases soil bulk density [141]. However, while a high rate of nutrient release from fast decomposition occurs only when the organic substrate is rich in nutrients and has low C:N and C:P ratios, the net nutrient release from organic matter is a function of decomposition ratios of organic matter fractions and uptake of nutrients by the growing biomass [142]. Dipeolu *et al.* [143] reported that 43% of respondents in a survey agreed that organic vegetables were more wholesome than conventionally grown ones and 33% were prepared to pay 23–27% premium on different organic vegetables. Pawpaw orchards treated with OMF showed significantly ($P \leqslant 0.01$) higher P, K, Na and organic matter in post cropping soil fertility analysis compared with soil with applied inorganic fertilizer NPK 15:15:15 [102]. The orchards planted with cultivation of 'Homestead crop mixture' resulted in lower soil bulk density (SBD) and significantly lower organic matter percentage than 'Sunrise crop mixture', probably due to greater rooting activity. However, post cropping soil Na and Mg was lower after 'Sunrise crop mixture' than after 'Homestead crop mixture', while soils of orchards planted with pawpaw grown in monoculture were higher in SBD [102].

## 4 Fruit production and productivity

### 4.1 Crop production under rain-fed conditions

Crop production under rain-fed agriculture is prone to soil water stress, this notwithstanding, improved productivity and a synergistic effect of optimum combination of organic resources and fertilizers has been reported to improve water use efficiency under these conditions [144]. Crop performance varies between mono-cropping or multi-cropping systems due to intra- and inter-specific competition. Crops with incomplete foliage cover such as juvenile pawpaw in monoculture during a considerable period of their growth cycle may lose up to 50% of total water use (evapo-transpiration or ET) by soil evaporation (Es) [67], while in a crowded community at higher planting densities or in poly-culture, each plant is restricted to less than its potential growth rate and final size [85, 145]. The beneficial effects of intercropping systems compared with sole cropping with regard to increased productivity, weed control and diversification of outputs have been reported by many researchers [146–151]. The resulting ecological relationships could be competitive or complementary in nature. However, the planting of several crops, which differ in height, root development, and light requirement, allows for a more efficient use of solar energy, soil nutrients, and water [152].

The various ecological relationships in crop mixtures resulting in reduced crop yields have been associated with less soil water exploited by component crops, shading close to taller crops, phytotoxins in the soil, and competition for nitrate-nitrogen among component crops [153–157]. Nonetheless, profitable intercropping of pawpaw specifically is related to its compatibility with other crops in terms of favourable competition for soil nutrients, soil moisture, and light. Olasantan [148] observed that vegetable crops, including cucumber, occupy a valuable ecological niche in tropical agriculture and play a significant role in the eco-physiology of mixed systems. According to Agboola [158], farmers in Southern Nigeria have developed a sophisticated system of mixed tree and arable cropping that mimics the multi-storey vegetation found in a rain forest. Here the tree components in the mixture are usually not arranged systematically but are scattered and sufficiently widely spaced to allow the introduction of arable crops. Hence pawpaw is rarely grown in pure stands but usually found in mixtures with other crops of upper storey perennials, usually taller trees such as oil palm (*Elaeis guineensis* Jacq.), middle storey perennials such as *Citrus* spp., and lower layer annuals and biennials including okra (*Abelmoschus esculentus* (L.) Moench.), and pepper (*Capsicum frutescens* L.) [158].

Successful crop mixtures exploit variation between component crops by extending the sharing of available resources over time and space [159], hence the onset of competition between intercrops can be delayed by judicious choice of relative planting dates. However, physiologically related growth depression reported in pawpaw [64,93] at the physiological transformation from vegetative growth to flowering/fruiting showed that 'Homestead selection', being a heavy feeder, had a growth depression that was not observed in 'Sunrise Solo' [160], hence okra planted late (vegetable introduced after pawpaw) was injurious to 'Homestead selection' but not to 'Sunrise Solo'. This indicates that the most appropriate and safe time to introduce intercrops into pawpaw orchards is at early (vegetable introduced before pawpaw) or simultaneous planting periods.

Apart from macro-environmental variation, a micro-environment exists where competing plant species coexist having vertical leaf profiles that overlap, with both plant species shading each other as well as themselves. In such a case, either through horizontal space or time, a vertical gradient in light intensity is created by the plant leaves that form the foliage canopy [161, 162]. Plants that deploy leaves high within the canopy expose them to high irradiance that produces rapid photosynthesis but pay the considerable energetic cost of growing and then maintaining tall stems to support these leaves compared with plants whose leaves are nearer the ground and intercept less sunlight and experience slower photosynthesis, but with the short stems which reduce the energetic cost [163]. Interception of sunlight determines production rate. The potential production rate of full cover crops correspond to more than 3 g biomass $MJ^{-1}$ solar radiance and the maximum efficiency of energy storage in chemical bonds of biomass is near 5% total radiation [67]. Light interception by a canopy depends on leaf area index (LAI) which has been regarded a stress indicator that can be used to compare canopy development over time [164, 165]. Thus, higher total LAI recorded for pawpaw with early cucumber introduction than in monocrop pawpaw was indicative of an ameliorative influence of cucumber on the environment [166]. This confirmed findings of Ikeorgu [167] and Ossom [168]. However, the observed growth retardation of unstressed pawpaw caused by late cucumber introduction could be due to competition for nutrients at a critical growth period of both pawpaw and cucumber which coincided with one another [166].

### 4.2 Crop productivity and economic potentials

Productivity is explicitly defined by the yield of useful product per unit land area while considering the efficiency of various inputs contributing to the yield [169]. Productivity in itself is considered as a very important property of farming system alongside stability and sustainability of the system. The important criteria involved in making comparisons among intercropping systems and in comparing them with sole cropping are varied and include such indices as land equivalent ratio LER [170–172], aggressivity value [173], relative crowding coefficient RCC [174], area × time equivalency ratio ATER [176], land equivalency coefficient LEC [176], area harvest equivalency ratio AHER [177], monetary equivalent ratio MER [178], among others. A widely used indicator of productivity or over yielding developed for the Replacement Series (RS) design [179–181] is the land equivalent ratio (LER) [182, 183]. Similar to the relative yield total (RYT) introduced by De Wit and van den Bergh [184], the LER is defined as:

$$LER = \frac{Y_{ab}}{Y_{aa}} + \frac{Y_{ba}}{Y_{bb}}$$

where $Y_{ab}$ and $Y_{ba}$ are the individual crop yields in intercropping and $Y_{aa}$ and $Y_{bb}$ are the yields in sole crop [170, 171].

Aiyelaagbe and Jolaoso [147] reported an improved Land Equipment Ratio (LER) in pawpaw mixtures with water melon (*Colocynthus citrullus*), okra (*Abelmoschus esclentus* Moench), sweet potato (*Ipomoea batata*), bush greens (*Amaranthus hybridus*), Jews' mallow (*Corchorus olitorious*) and scarlet eggplant (*Solanum gilo* Raddi, syn. *S. aethiopicum* L.). Calculation of land equivalent ratio (LER) showed that resources were used from 17 to 31% more efficiently for growth by crops in mixtures than by sole crops [185]. John and Mini [186] observed favorable LER, land equivalent coefficient LEC, area × time equivalency ratio ATER, aggressivity values, and total biomass production for the intercropping of okra with cucumber, implying intrinsic advantages over sole crops.

Various studies on cropping systems have reported the retardation effects of intercropping systems on both vegetative and reproductive growth of component crops in mixtures compared with monocrops [37, 160, 166, 187, 188, 190]. Intercropping significantly decreased pawpaw plant height, stem girth, number of leaves, leaf area and canopy spread in the first year while it sustained LER. The significant and non-significant difference in leaf area index (LAI) as a stress indicator at juvenile and mature pawpaw stages respectively indicated the level of stress imposed on pawpaw cultivated in crop mixtures and at different times of intercropping [190]. The results showed that pawpaw could be intercropped with vegetables at the early vegetative stages to sustain land utilization as well as total productivity [37]. The lower growth responses of pawpaw cultivated as a sole crop than in a mixture with cucumber indicated an ameliorative effect of cucumber. However, late introduction of cucumber into pawpaw at a critical growth period for both crops caused significant growth reduction of both component crops. 'Sunrise Solo' in mixtures produced more fruit, greater fruit yield and higher vegetable relative yield total (RYT) value than 'Homestead selection' but lower pawpaw RYT value [190]. The lower profit margins obtained from one intercropping cycle than from sole cultivation was eliminated with two intercropping times due to the higher yield of cucumber with early or simultaneous introduction [166, 190].

Intercrop productivity depends on the genetic constitution of component crops, growth environment (atmospheric and soil) and agronomic manipulation of the microenvironment [191]. Hence intercrops are most productive when their component crops differ greatly in growth duration so that their maximum requirements for growth resources occur at different times. "Additive" intercrops are those where growth durations of component crops are similar and the crops compete more intensely for available resources but may nevertheless be productive, particularly where growth resources are more completely captured than in corresponding sole crops, while "Replacement" intercrops involve situations where the non-replenished growth resources are utilized too rapidly, and the less-competitive component may suffer greatly so no productivity gain is experienced in high-yielding environments [191].

### 4.3 Compatibility with component crops

Manipulating resource input into crop mixtures to an optimum level across seasonal variations highlighted the yield potential of pawpaw in crop mixtures compared with that obtainable with sole cropping [192]. With pawpaw mixtures, Aiyelaagbe and Jolaoso [147] recorded higher productivity with yield advantages of 3.86, 3.13, 2.06, 1.86, 1.60 and 1.54 when intercropped with okra, water-melon, sweet potato, bush greens, jews' mallow and scarlet eggplant, respectively; indicating that all the combinations were more advantageous than the monocrop of pawpaw. However, although sweet potato effectively controlled weeds in pawpaw plots, both sweet potato and scarlet eggplant caused marked reduction in the

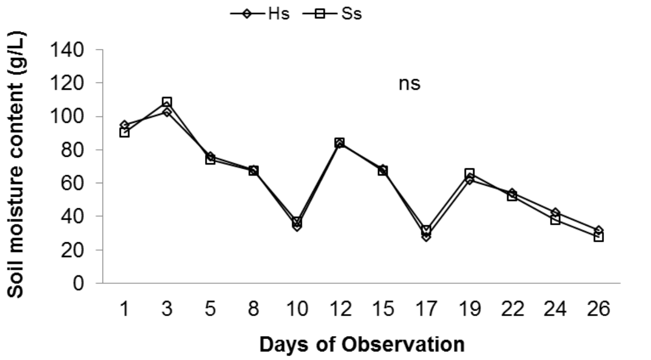


**Figure 5.** Soil moisture content observed under pawpaw varieties. Hs = 'Homestead selection'; Ss = 'Sunrise Solo'. Source: Olubode *et al.* [102].

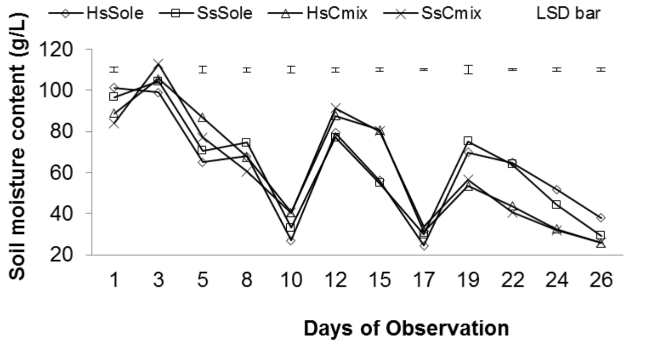


**Figure 6.** Soil moisture content observed under pawpaw/cucumber mixtures. HsSole = 'Homestead selection' monocrop, SsSole = 'Sunrise Solo' monocrop, HsCmix = 'Homestead selection'/cucumber mixture, SsCmix = 'Sunrise Solo'/cucumber mixture. Source: Olubode *et al.* [102].

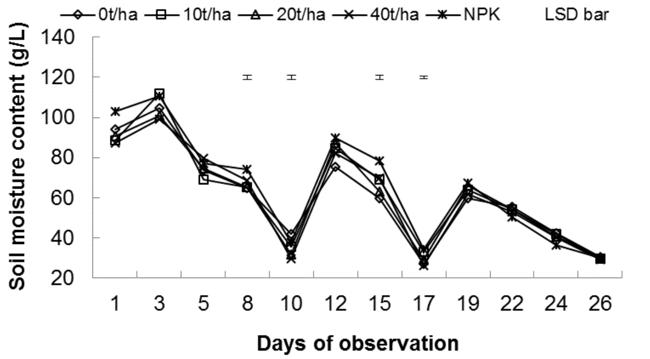


**Figure 7.** Soil moisture content observed under applied manure rates. 0 t $ha^{-1}$ = unfertilized control, organic fertilizers at 10 t $ha^{-1}$, 20 t $ha^{-1}$ and 40 t $ha^{-1}$ rates, and NPK = inorganic fertilizer at 50 g $plant^{-1}$ $month^{-1}$. Source: Olubode *et al.* [102].

fruit yield of pawpaw. Furthermore, intercropping 'Sunrise Solo' with pumpkin (*Curcubita maxima*) effectively controlled spear grass (*Imperata cylindrica*) infestation which was at par with hoe weeding or application of Delsate™ herbicide. Among the treatments, only intercropping with white pumpkin significantly decreased leaf area of papaya with a 13% decrease in productivity compared with that of chemically weeded plots [193]. In addition to weed control, intercropping with pumpkin conserved soil moisture, increased earthworm activity and decreased diurnal maximum temperature [194]. Weed control in fruits orchard accounts for 30% of operational costs [195]. Land use system involving [arable crop + teak + pawpaw] gave the highest average net return per hectare after 7 years followed by treatments having subabul grass (*Leucaena leucocephala*) compared with treatment with only arable crops [196]. In a field trial, Ler *et al.* [197] observed that the most productive crop rotation for intercropping in pawpaw plantation were crop rotations of summer greengram/mustard greens (*Vigna radiata*/*Brassica juncea*) and greengram/wheat intercrops because of their maximum productivity measured in terms of wheat equivalent grain yield.

The intercropping of component crops is practised with the sole aim of maximizing plant cooperation for maximum crop yield [198]. Canopy height is one of the important features that determine competition ability of plants for light [199]. The taller component crop intercepts the major share of the light such that growth rates of the two components will be proportional to the quality of the photosynthetically active radiation intercepted [200]. The early (okra introduced before pawpaw) and simultaneous introduction of okra into pawpaw orchards were significantly ($P \leq 0.05$) better than late introduction (okra introduced after pawpaw) in 'Homestead selection' but not in 'Sunrise Solo' pawpaw [160], while vegetative and reproductive growth of 'Sunrise Solo' pawpaw, okra and cucumber component crops were significantly retarded ($P \leq 0.05$) compared with monocrops in all components of the system [166]. Although planting vegetables before pawpaw or planting both simultaneously significantly enhanced flowering of pawpaw ($P \leq 0.05$) compared with late intercropping, the fruit yield of pawpaw was higher ($P \leq 0.05$) with late intercropping (42.7 t $ha^{-1}$) than with simultaneous and early intercropping (41.7 and 40.5 t $ha^{-1}$, respectively) [166].

The ameliorative effect of cucumber on the microclimate alongside productivity advantages also showed that cucumber could be adopted by pawpaw growers as a relatively compatible intercrop of pawpaw [102, 168]. Compatibility between pawpaw and cucumber as intercrops especially occurred when higher soil moisture content (*figures 5–7)* and cooler soil temperatures (*figures 8–10)* resulted in more conducive environment for improved growth and yield of the component crops [168]. The relative yield total (RYT) for okra in two years indicated that 'Sunrise Solo' was more conducive for okra productivity than 'Homestead selection' [160]. However, introducing okra late depressed plant height, canopy spread, and leaf area of both 'Homestead selection' and 'Sunrise Solo' pawpaw compared with early or simultaneous introduction [160]. Nonetheless, responses of an okra intercrop in juvenile pawpaw confirmed an earlier report by Olasantan [201] that in sole and mixed stands with cassava, significant season x population and season x sowing date interactions occur and there are good prospects and potentials for okra production, but only with specific planting dates and population densities in both the early and late rainy seasons in south western Nigeria.

Moreover, the soil bulk density observed in pawpaw varietal trials and in crop mixtures with vegetables showed the

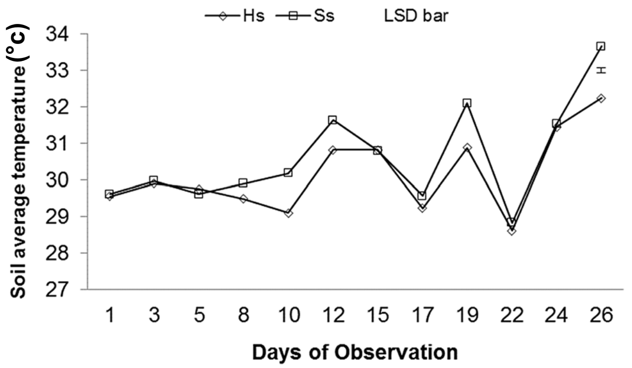


**Figure 8.** Soil average temperature observed pawpaw varieties. Hs = 'Homestead selection'; Ss = 'Sunrise Solo'. Source: Olubode *et al.* [102].

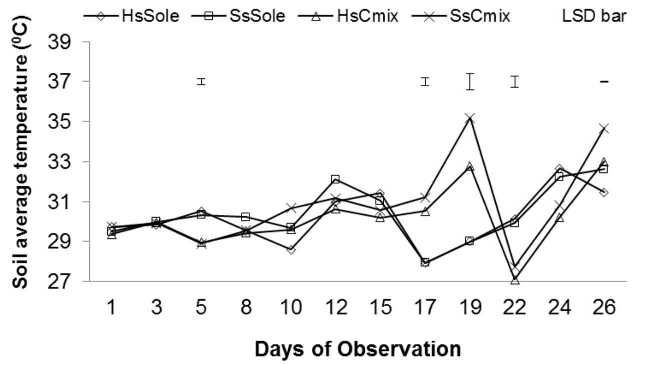


**Figure 9.** Soil average temperature observed under papaya / cucumber mixtures. HsSole = 'Homestead' monocrop, SsSole = 'Sunrise Solo' monocrop, HsCmix = 'Homestead Selections' / cucumber mixture, SsCmix = 'Sunrise Solo' / cucumber mixture. (Source: Olubode *et al.* [102]).

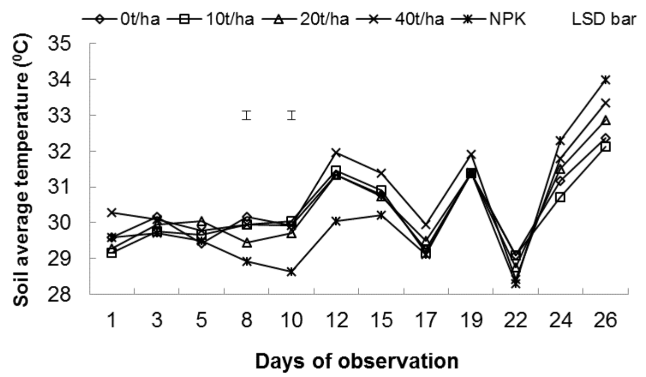


**Figure 10.** Soil average temperature observed under applied manure rates. 0 t $ha^{-1}$ = unfertilized control, organic fertilizers at 10 t $ha^{-1}$, 20 t $ha^{-1}$ and 40 t $ha^{-1}$ rates, and NPK = inorganic fertilizer at 50 g $plant^{-1}$ $month^{-1}$. Source: Olubode *et al.* [102].

influence of the different rooting activities of the varieties (*figures 11–13*) [102]. This influence appeared related to varietal relative below-ground crop growth responses which contributed to yield differences in the varieties.

### 4.4 Maximizing the benefits of cropping systems

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 intercrops before the main crop pawpaw is harvested [37, 147]. In a three year study, significant varietal differences were reported in the response of pawpaw to intercropping with cucumber. 'Sunrise Solo', with average fruit weight of 380 g produced 74.8 fruits $plant^{-1}$, while 'Homestead selection' with average fruit weight of 580 g, produced 44.6 fruits with corresponding fruit yields of 53.3 and 37.9 t $ha^{-1}$, respectively [192]. Lower profit margins were obtained with one than with two cycles of intercropping or sole pawpaw due to higher yield value of cucumber (*figures 14, 15*) [166, 190]. Yield, economic value, and profit margins obtained for okra and cucumber differed markedly. The indication was that intensification of cropping system by maximizing the available land space and time, by using different planting dates for introducing three months duration vegetable crops in long duration pawpaw orchard, and by increasing the number cycles of intercropping within the same main crop might be more beneficial than sole or one time intercropping [166].

Highest profit margin was recorded for simultaneous planting followed by early introduction of okra intercrop in 'Homestead selection' pawpaw (46.35 and 43.20%, respectively) or in 'Sunrise Solo' pawpaw (38.58 and 38.23%, respectively), while late introduction had the least profit margin in both pawpaw cultivars [160]. These were all lower than with pawpaw intercropped with cucumber. Thus the economic returns calculated for mixed pawpaw indicated a profit margin under sole pawpaw (64%), sole cucumber (56%) or sole okra (45%) compared with 67, 74 and 78% obtained with one, two or three cropping times with cucumber [166].

### 4.5 Effect of seasonal variation on pawpaw based cropping system

The environmental conditions of temperature and soil moisture influence the partition of assimilates into either the vegetative or reproductive sink. With LAI as a stress indicator, mature 'Homestead Selection' had lower vegetative growth in years two and three experiments due to environmental stress while mature 'Sunrise Solo' recorded no stress across the years [192]. The influence of lower temperature on pawpaw flower induction was observed in a field experiment where the third year, which had the lowest maximum and minimum temperature, had the highest cumulative number of flowers [192], confirming the report by Olasantan [201] that minimum temperature is important in floral induction, although the influence of warmer temperature more than moisture availability was also observed on fruit set [192]. The more flowers, more fruits and heavier fruit yield of 'Sunrise Solo' and monocrop pawpaw than of 'Homestead Selection' and pawpaw in mixture indicated the greater yield potential of 'Sunrise Solo' and the yield reduction caused by intense competition with

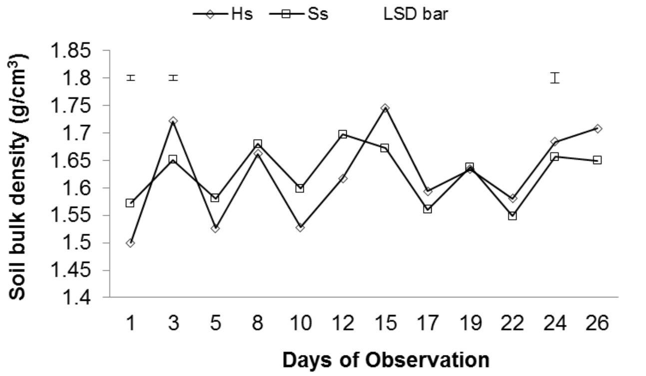


**Figure 11.** Soil bulk density observed under Homestead and Sunrise pawpaw varieties. Hs = 'Homestead Selection'; Ss = 'Sunrise Solo'. Source: Olubode *et al.* [102].

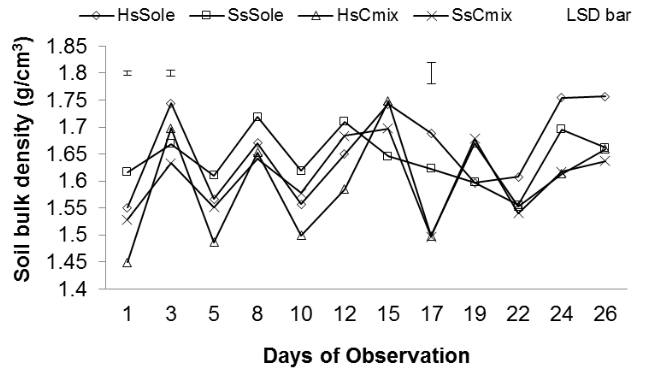


**Figure 12.** Soil bulk density observed under papaya/cucumber mixtures. HsSole = 'Homestead' monocrop, SsSole = 'Sunrise Solo' monocrop, HsCmix = 'Homestead Selections'/cucumber mixture, SsCmix = 'Sunrise Solo'/cucumber mixture. (Source: Olubode *et al.* [102]).

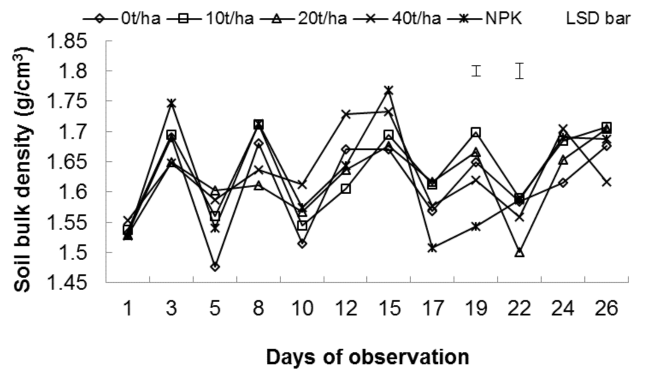


**Figure 13.** Soil bulk density observed under applied manure rates. 0 t $ha^{-1}$ = unfertilized control, organic fertilizers at 10 t $ha^{-1}$, 20 t $ha^{-1}$ and 40 t $ha^{-1}$ rates, and NPK = inorganic fertilizer at 50 g $plant^{-1}$ $month^{-1}$. Source: Olubode *et al.* [102].

an intercrop for growth resources. Despite the LER > 1.00 recorded over three years (1.37, 1.57, and 1.28) indicating significant seasonal differences in productivity responses among pawpaw varieties, a higher RYT and LER for 'Sunrise Solo' and pawpaw/okra mixtures than for 'Homestead Selection' and the monocrop pawpaw indicated both the higher productivity of 'Sunrise Solo' and the significant contribution effect of the okra intercrop in the overall productivity of the crop mixtures [192].

The high crop production and productivity potentials of pawpaw, which are near optimum in the even distribution of environmental moisture in triple peak rainfall pattern of year two experiment compared to the higher rainfall but with less even spread of environmental moisture of year three experiment indicated the essence of a balanced pawpaw productivity requirement [192]. Pawpaw in crop mixtures would need a sustained soil moisture content and/or supplemental moisture application to support component crops and thus alleviate the competitive needs for moisture in a crowded plant community as described by Loomis and Connor [67]. For example, pawpaw in crop mixtures with cucumber initially had higher soil moisture, lower temperature and lower bulk density than monocrop pawpaw, while under prolonged moisture stress the reverse was obtained. The inclusion of trailing plants such as cucumber (*Cucumis sativus* L.) [168] in pawpaw mixtures provides a conducive soil microclimate including higher moisture content, cooler temperatures, and effective weed suppression. As pawpaw is highly responsive to soil moisture stress, this would indicate that at certain periods of growth, pawpaw would benefit from a compatible companion crop to stabilize the microclimate in a sustainable manner.

### 4.6 Fruit handling, postharvest and storage techniques

Pawpaw has a high yield potential due to its precocious bearing and indeterminate growth habit [39]. The storage life of harvested pawpaw fruit is short due to dehydration losses and rotting leading to revenue losses to farmers engaged in its production [202]. However, pawpaw seeds, when kept air-dry in airtight containers can retain their viability for 2–3 years [203]. Among the most important factors that determine storage life and final fruit quality is the maturity of pawpaw fruit at harvest [5], as immature fruits are more subject to shrivelling and mechanical damage, and are of inferior flavour when ripe. On the other hand, overripe fruits are likely to become soft and mealy with insipid flavour soon after harvest [5]. One of the main causes of postharvest losses is mechanical damage to pawpaw skin through poor handling, unsuitable containers, improper packaging, and jostling of fruits during transportation thus causing bruising, cutting, breaking, impact wounding and other forms of injury [204, 205].

High temperature, low atmospheric humidity and physical injury alter the natural deterioration rate through physiological changes, which can also occur spontaneously by enzymatic action leading to over ripening and senescence, a simple aging phenomenon [204]. Ripe, full-color fruit can be held for more than 1 week at 1–3 °C. Pawpaw fruit at color-turning (break) stage can be stored at 7 °C for 14 days and will ripen normally when transferred to room temperature [206, 207]. At 7–10 °C,

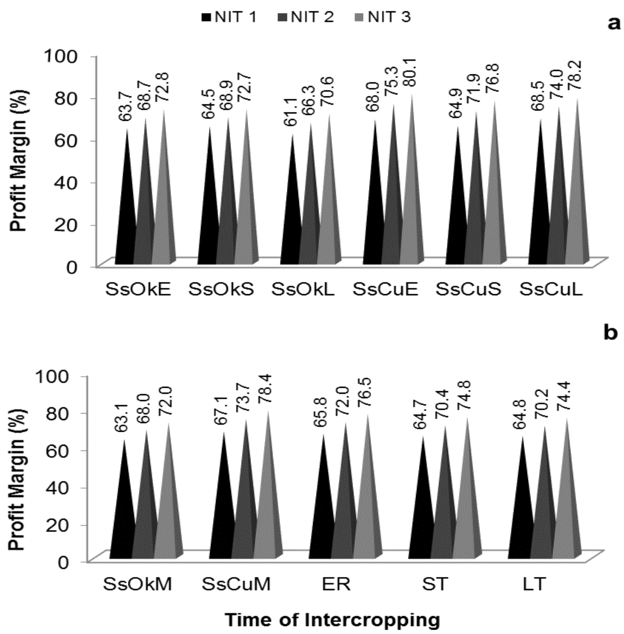


**Figure 14.** Profit margin (%) obtained for 'Sunrise' pawpaw in crop mixture with cucumber and okra introduced at different times. NIT 1 = One Intercropping Time, NIT 2 = Two Intercropping Times, NIT 3 = Three Intercropping Times, SsOkE – 'Sunrise'/Okra Early, SsOkS – 'Sunrise'/Okra Simultaneous, SsOkL – 'Sunrise'/Okra Late, SsCuE – 'Sunrise'/Cucumber Early, SsCuS – 'Sunrise'/Cucumber Simultaneous, SsCuL – 'Sunrise'/Cucumber Late,, SsOkM – 'Sunrise'/Okra Mixture, SsCuM – 'Sunrise'/Cucumber Mixture, ER – Early, ST – Simultaneous, LT – Late. (Source: Olubode *et al.* [166]).

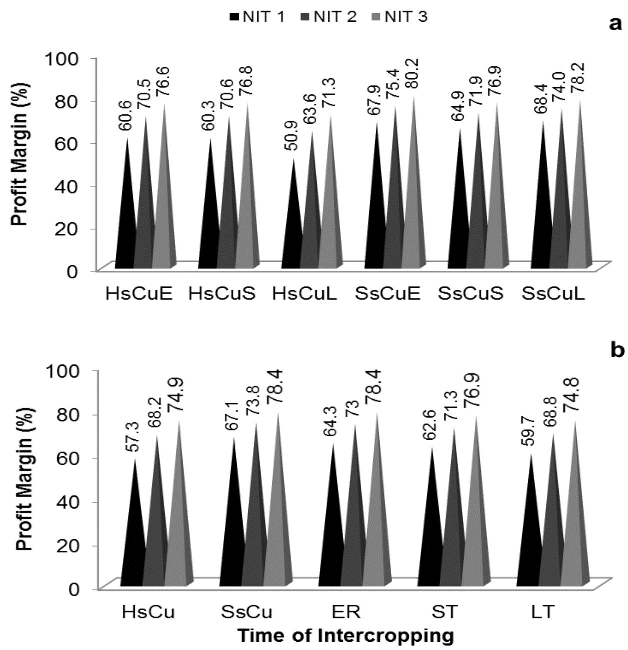


**Figure 15.** Profit margin (%) obtained for 'Homestead selection' and 'Sunrise' pawpaw in crop mixture with cucumber introduced at different times. NIT 1 = One Intercropping Time, NIT 2 = Two Intercropping Times, NIT 3 = Three Intercropping Times, HsCuE – 'Homestead'/Cucumber Early, HsCuS – 'Homestead'/Cucumber Simultaneous, HsCuL – 'Homestead'/Cucumber Late, SsCuE – 'Sunrise'/Cucumber Early, SsCuS – 'Sunrise'/Cucumber Simultaneous, SsCuL – 'Sunrise'/Cucumber Late, HsCu – 'Homestead'/Cucumber Mixture, SsCu – 'Sunrise'/Cucumber Mixture, ER – Early, ST – Simultaneous, LT – Late. (Source: Olubode *et al.* [190]).

storage-life is limited by chilling injury while at 10–13 °C (50–55 °F) ripening occurs slowly [207]. However, since sugar develops only at the onset of ripening process any attempt to harvest at the earlier stages of fruit maturity meant to achieve better storage life will be at the expense of quality [208] indicating the reason why pawpaw picked at a quarter to full yellow colour taste better [2] and reached peak flavor when the skin attains 80% yellow color [209] whereas those picked mature-green to one quarter yellow do not increase in sweetness after harvest.

Pawpaw fruit treated with aqueous seed extract and papain exhibited remarkable mycelial inhibition of fungal pathogen causing pawpaw fruit rot with mean zones of inhibitions between (0.23–1.73 mM) [210]. Pawpaw fruit coated with aloe gel (AG) alone and mixed with pawpaw leaf extract (PLEAG at 1:1 v/v) maintained their shelf life for 12 days and decayed only after 16 days. There was 27% disease incidence with AG and only 13% with PLEAG coated fruits compared with 100% for the untreated control during the same storage period [211]. The pre-treatment of fruits with hot water followed with chlorine can also extend the percentage of pawpaw fruit successfully preserved by 8% over untreated fruits and has been a method reported to kill insects and inhibit microbial growth [212, 213]. Similarly, the treatment of fruits with calcium based salts have extended storage life while sodium salts, particularly sodium chloride, resulted in both physical and microbial deterioration of the fruit [214, 215]. Calcium chloride was reported to inhibit fungal conidia germination and extend pawpaw storage life by 15 days, and reduced the incidence of weight and firmness loss. Since postharvest cooling removes field heat in fruit, proper cooling should suppress enzymatic degradation, lower water loss in fruit thereby prolonging good fruit quality before arrival to consumers' tables [216].

However, in many developing countries postharvest handling procedures are poorly developed and agriculture may be characterized as disjointed because production is not closely integrated with marketing [217]. The lack of availability of proper storage and transportation facilities and improper handling methods result in high levels of damage during harvesting and transit [218]. Estimated losses which may be regarded as normal at 10% may run up to 80% in developing countries [3]. Hence about 5–25% of the produce (fruit and vegetables) leaving the farm gates may never be consumed but is thrown away. Underlying these problems is poor government intervention, typical of most tropical areas with inadequate extension of information and absence of capacity building programmes to bridge the knowledge gap among farming communities. This has been compounded in some countries by an overdependence on non-agricultural sources of revenue such as oil whereas some governments have successfully established functional marketing board that link farm with markets. This is confirmed by Aiyelaagbe [8] reporting that the challenge of raising productivity of horticultural crops is daunting and only an effective policy environment will allow horticulture to contribute effectively to healthier and improved livelihoods in developing countries such as Nigeria.

The most important aspect of post-harvest handling is storage as the storage life of most fruits is short due to dehydration, losses and rotting [219]. The most commonly used storage techniques for pawpaw include refrigeration which controls temperature and humidity by mechanical means; and controlled atmosphere storage which controls the concentration of oxygen and carbon dioxide, in addition to temperature and humidity. These methods are both categorised as "high-tech" and likely to be available only to companies or communally grouped farmers producing the same varieties for specific markets in medium to high quantities. In contrast, "low-tech" storage methods available to individuals include the zero energy evaporative coolant structure promoted by the Nigerian Stored Products Research Institute (NISPRIN) in Nigeria [7].

#### 4.6.1 Refrigerated storage

Ripe pawpaw fruits will store successfully at low temperatures. Medina De La Cruz *et al.* [203] stated that the recommended storage temperature for pawpaw is 10 °C and storage of unripe pawpaw below this temperature will result in chilling injury with symptoms of surface pitting, discoloration of the peel and flesh, incomplete ripening, poor flavour and increased susceptibility to disease. Nonetheless, different maturity stages require different storage temperatures for shipment. Pawpaw fruits above colour break are held at 8 °C, in which case the fruits keep for 4 weeks, but this temperature is detrimental for those at mature green stage for which the safe temperature appears to be around 10 °C [208], while pawpaw at colour-turning stage can be stored at 7 °C for 14 days and will ripen normally when transferred to room temperature [206, 207].

#### 4.6.2 Controlled atmosphere storage

Controlled atmosphere storage of pawpaw can be effective only when the $CO_2$ concentration is kept below 1% and it is used along with low temperature, hot water and ethylene bromide treatments [208]. Shelf life extension of 1 to 1.5 days was obtained when pawpaw were stored at 12 °C in 1 to 1.5% $O_2$ for 6 days [220] cited in [221]. Low $O_2$ (1 to 5%), with or without high $CO_2$ (2 to 10%), reduces decay [222] and delays ripening [206, 223]. High $CO_2$ (30%) adversely affects internal color, aroma, and flavor, while there is no residual effect of 10% $CO_2$ on decay control, though skin de-greening is delayed. Fruit stored at 10 °C and 98% relative humidity and low pressure of 20 mm Hg, ripened more slowly than fruit at normal atmospheric pressure. Low-pressure storage appears to suppress disease development [221, 224].

#### 4.6.3 Evaporative Coolant Structure (ECS)

Compared with the high cost involved in developing cold storage or controlled atmosphere storage, the zero energy evaporative coolant structure (ECS), a humidity chamber promoted by the NSPRI and described by Babarinsa and Nwangwa [225] not only reduces the storage temperature but also increases the relative humidity in storage, essential for maintaining the freshness of the commodities. The ECS thus has potential for use for short term preservation of vegetables and fruits soon after harvest [226]. There are several shapes and sizes of ECS but all utilise the same principle [227] and are ideal for storing fruit in developing country where farmers have limited resources. In addition, ECS are beneficial and convenient for rural farmers because they are cheaper, accessible and can store harvested produce well for considerable periods [7, 202, 228]. 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 [229]. "Wet-jute-box" was also considered a more efficient method than "pot-in-pot" for produce preservation [230]. 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 product weight loss (5.95%) than in ambient conditions (18.39%) [231, 232].

### 4.7 Call for new production strategies

The observed dwindling revenue from pawpaw fruit production [2, 15] calls for the adoption of new production strategies to improve productivity and profitability. Improving the poor produce quality and financial losses that result from produce spoilage along the production chain, encountered mainly by the rural farmers who produce most of third world produce will need direct government intervention. Produce spoilage could be temporarily delayed and/or significantly reduced before delivery to destination points. Farmers need exposure to modern production techniques and direct government intervention by improving rural extension services will introduce farmers to improved production techniques that will ensure high grade produce for increased local markets and for export. Intervention by direct purchase and distribution of quality harvested produce, and the provision of modern storage facilities to the organized sector for prolonged shelf live is also possible through organised sharing of manageably sized storage facilities, using larger communal groups and/or agricultural cooperatives/units. Fair and farmers friendly policy will provide environment for improved value chain and protect rural farmers from exploitation by aggressive business men. This 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.

## 5 Conclusion

Although seasonal variation can have a significant effect on crop production and productivity, knowledge driven cropping systems can manipulate production factors to a better advantage. The identification of compatible crops to maximise resource use efficiency and intensification of intercropping systems through effective use of short duration crops in mixtures with long duration crops will effectively utilize the variability in component crop growth habits. At the same time, the introduction of environment friendly soil amendment practices will help to replace soil nutrients taken up by plants and sustainably improve soil health. Moreover, the intensification of cropping will require the manipulation of intercrops at the population level to optimise nutrient use efficiency, whereas most previous crop spacing recommendations have been based on trials involving sole cropping. Thus undertaking practicable and result-oriented crop placement trials will assist in the improvement of the productivity of cropping systems. Lastly, the aspect of governmental support to growers through enacting farmers friendly policy, better and more efficient extension programmes, farmers' development through capacity building, and placement of infrastructures required to better link farms with markets and to extend the storage life of products will encourage more production, reduce the rural to urban drift and bring agriculture back to its enviable position in the developing countries that have been well favoured with natural resources for profitable farming ventures.

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