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Review Article

Radiation Dynamics on Crop Productivity in Different Cropping Systems

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Global demand for food has always been on the increase due to the increase of the population in this world. Intercropping is one of the alternatives of agronomic practices that is widely practiced in ensuring food security and enhancing yield stability. Strip, mixed, and relay intercropping can be practiced to increase crop production. In addition to achieving a successful intercropping system, factors such as suitable crops, time of sowing, maturity of the crop, and plant density need to be considered before and during planting. Besides, practiced intercropping becomes a useful cropping system to increase efficient resource utilization, enhance biodiversity, promote soil health, enhance soil fertility, erosion control, yield advantage, weed, pest, and disease control, insurance against crop failure, ecosystem and modification of microclimate, market instability, and increase farmers income. Crop productivity in any types of cropping system implemented relies primarily on the interception of photosynthetically active radiation (PAR) of crop canopy and conversion of intercepted radiation into biomass or known as radiation use efficiency (RUE). Both PAR and RUE are important measurements that have significant roles in crop growth and development in which the accessibility of these radiation dynamics is connected with the leaf area index and crop canopy characteristics in maximizing yield as well as total productivity of the crop component in intercropping systems.

1. Introduction

The fast-growing world population has been quoted to be the case for the increase in large-scale farming and agro-industries in order to meet the demand for food of the larger population [1]. A majority of the rural populace of developing countries are engaged in the agricultural sector for their livelihood and subsistence. Intercropping is one of the alternatives involving agronomic practices in ensuring food security and enhancing yield stability [2]. This was because a cropping system of intercropping can secure food supply to feed the world population by providing for almost 15–20% additional yield based on the practice of growing more than two types of crops at the same time [3–5]. In addition, practicing only sole cropping in any crop planting scheme has significant problems and could not ensure a continuous food supply as there is a high risk of crop failure due to biotic and abiotic factors such as flood, pest and disease infestation, and soil acidity or alkalinity [6].

Intercropping is a traditional agriculture practice and becomes a popular farming system among tropical small-scale farmers [7]. It gives many biological, ecological, and socioeconomic benefits compared with sole cropping [8]. Intercropping also promotes sustainable agriculture through sustaining the productivity [5], maintaining the ecological balance [9], and using the environmental resources efficiently [10].

Intercropping is said to increase productivity along with sustainability per unit area of land [8] and intensify the production of crops [11]. Increasing crop productivity is the major aim of farmers and agriculturists alike. Intercropping allows farmers to stabilize their incomes as they can benefit from the main crops and other component crops [10, 12]. Besides, it also ensures the farmer's higher return over time [13].

2. Concepts of the Intercropping System

2.1. Types of Intercropping. Intercropping is growing two or more crop species together at the same time on the same piece of land [14], in which the crops have different productivity and growth habits [15]. To ensure the increment of crop yield, mixed, relay, and strip intercropping can be practiced through resource facilitation and partitioning [16, 17].

Mixed intercropping is the practice of growing two or more crops simultaneously in the available space without arrangement in distinct rows or divisions [5, 18] (Figure 1(a)), whereas strip intercropping is growing two or more plant species in distinct alternate rows simultaneously [17] (Figures 1(b) and 1(c)). Relay intercropping involves a cropping pattern in which two or more crops are cultivated together, and the life cycle of one crop overlaps that of another crop [17, 19].

2.2. Basic Principles of Intercropping. In achieving successful intercropping system, suitable crops and time of sowing [10], maturity of the crop, and plant density [22] need to be considered before and during planting.

2.2.1. Suitability of Crops. Not all crops are compatible to be intercropped; hence, it is important to choose the best crop combination to improve productivity [23]. Choose crops with minimum plant competition, not only through spatial arrangement and planting density but also the choice of crops which are able to exploit soil nutrients better [22]. For example, growing cereal and legume crops in the intercropping system would be valuable for utilizing different resources of nitrogen. According to Dwivedi et al. [10], cereal crops may be competitive for soil mineral nitrogen in comparison to legumes; however, legume crops are able to fix nitrogen taken from soil through the process of symbiosis. Punyalue et al. [24] reported corn grain yield increased by 31–55% when corn was intercropped with a legume crop. Besides, yam and pumpkin are also compatible to be intercropped. This was proven by Seran and Brintha [22] in which the yield was found to increase by 30–50%. However, some combinations are simply poorly intercropped together. For example, intercropping of maize with Mucuna (*Mucuna utilis)* led to yield reduction [10, 25]. This was in line with Bybee-Finley and Ryan [17] who concluded that inappropriate combinations of intercrops may lead to competition between two component crops, as one crop is believed to suppress the growth of another crop.

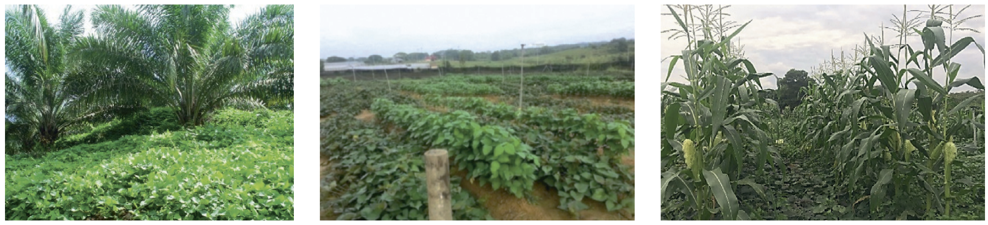
2.2.2. Time of Sowing. In intercropping, the combination crops are planted simultaneously in order to get better yield and keep the competition between the intercropped plants in balance. Some of the intercropped plants grow better when planted at the same time, and some perform differently at different planting times. Intercropped combination of maize and okra was reported to give better yield when planted at the same time [26]. Yield of maize grain was not affected when planted simultaneously with sweet potato, but affected the yield of sweet potato when planted later [22, 27, 21].

2.2.3. Maturity of the Crop. Intercropping of crops with different maturity dates should be practiced [28]. So as to minimize the competitions between crops, maximize the yield advantage, and make significant resource requirements at distinct times, the peak growth period of component crops should not occur simultaneously when growing two or more crops together. Crops with different maturity dates usually have different peak demands on nutrient, water, and light, which make them suitable to be intercropped [21, 29]. According to Brooker et al. [16], complimentary effects occurred between two component crops as the crops complimented each other when they had different growth performances and nutrient requirements on their demand for moisture, light, and nutrient. For example, in corn-green gram intercropping, at around 60 days of sowing, corn reached its peak light requirement, while the green gram was ready to be harvested [22].

2.2.4. Plant Population. Plant population is an important aspect to be considered to maintain high potential yield and reduce competition between intercrops [29]. Low population of plants may lower total plant yield [28]. However, if the crop was planted in full rates, the yield also may not be high due to the intense overcrowding. The statement was also supported by Seran and Brintha [22]—planting higher crop population might not result in higher yield due to the overyielding of the crops. Hence, it is vital to reduce the rate of the seedlings of each crop in order for the yield to turn up well. In a previous study, dry matter of maize was found to have decreased due to the increase of lablab population [30], and the number of leaves decreased as the plant density was high in maize-okra intercropping due to the presence of light and other resources' competition [31]. However, Brintha and Seran [32] found that there was no significant effect shown by radish in radish-*Amaranthus* intercropping due to the constant plant density of radish.

2.3. Benefits of Intercropping Practices

2.3.1. Efficient Resource Utilization. Intercropping is recommended to increase the efficiency of resource utilization over sole cropping [10, 33]; at the same time, it promotes interspecific interaction between component crops [34, 35]. It is envisaged that higher productivity can be achieved if there were more interspecific interactions between component crops in utilizing the limited available resources such as light and nutrients [36]. In addition, intercropping improves the radiation interception through more complete ground cover [37]. According to Kiseve [38], light intercepted was more efficient in intercropping compared to sole cropping. Liu et al. [39] were in agreement with this viewpoint since they observed that PAR and RUE intercepted were all greater in row intercropping corn-soybean and strip intercropping corn-soybean than in sole cropping



(a) (b) (c)

Figure 1: Examples of intercropping in (a) mixed intercropping of oil palm (*Elaeis guineensis* L.) and leguminous cover crop (*Mucuna bracteata* L.); (b) strip intercropping of soybean (*Glycine max* L.) into sweet potato (*Ipomoea batatas* L.); (c) strip-relay intercropping of corn (*Zea mays* L.) and sweet potato (*Ipomoea batatas* L.). Photographs by Mohd Anim [20] (a) and Nur Arina [21] ((b) and (c), respectively).

corn and sole cropping soybean. This was because the separation of the upper canopy of corn in strip intercropping resulted in higher PAR interception by soybean, and the large distances between corn strips were beneficial for increasing PAR interception for short statured crop in comparison to sole cropping [39].

2.3.2. Yield Advantage. Yield advantages occurred when environmental resources such as water, light, and nutrients were efficiently used by intercrops which could be converted into crop biomass [10, 40]. Land equivalent ratio (LER), a common index used to measure intercropping land productivity [8], may be used to verify the effectiveness of intercrops in utilizing environmental resources [41]. Intercrops achieve yield advantage when the LER value is greater than 1 [40], which indicates more interspecific facilitation than interspecific competition between two component crops [35]. Land equivalent ratio value less than 1 reveals yield disadvantage [42] due to more interspecific competition than interspecific facilitation between intercrops [35]. The LER of 1 shows no difference in the production of intercrops [43]. In a previous study by Nur Arina [21], sweet potato-sweet corn mixed intercropping and sweet potato-sweet corn relay intercropping systems showed LER value greater than 1 compared to sole cropping sweet potato and sole cropping sweet corn.

2.3.3. Economic and Social Benefits. A recent study has shown that intercropping for small-scale farming will continue to be more lucrative than single crops as they can produce more than one crop in one time period [33]. According to Undie et al. [36], intercropping also helps in securing the food output in developing countries in order to ensure continuous food supply. Besides, according to Yadav and Sonia [44], farmers who practice the intercropping system can get extra income as an additional benefit while, at the same time, allowing greater employment. Gebru [12] cited that intercropping also provides social benefits to small land holders and farmers, especially in updating traditional practices from the sole cropping system to multiple cropping systems in increasing yield and farm profits.

2.3.4. Pest, Disease, and Weed Control. Intercropping contributes to weed suppression as the system can lower the level of weed infestation naturally [45, 46]. Jabran et al. [47] cited that weeds become the major factor of yield losses when compared to the losses caused by pest and diseases. Eskandari [9] suggested that weed suppression was more efficiently carried out in wheat-faba bean intercropping than sole cropping wheat. Similar findings were revealed by Kumar et al. [48] and Matusso et al. [25] where corn-soybean intercropping showed less weed infestation when compared to sole cropping systems. Besides, intercropping with crops that produce allelopathic chemicals can help to smother the weeds [49]. For example, sweet potato has an allelopathic potential to compete with weeds for nutrients [49].

Intercropping can also control pest and disease incidence. The incidence of pests and diseases in the sole cropping system was shown to be greater than that in the intercropping system [28]. This was because intercrops can reduce the number of susceptible hosts [17]. Besides, intercropping the main crop with other trap crops or repellent crops helps in reducing the risk toward pest and disease incidence as it can function as a physical barrier against pest and disease spreads [22]. For an example, in the corn-napier strip intercropping system, napier acts as a trap crop to attract corn stem borers away from the main crop, and in the corn-legume intercropping system, legume (*Desmodium* spp.) acts as a repellent crop to repel corn stem borers from the main crop [17].

2.3.5. Erosion Control. Intercropping could result in greater erosion control than most of the sole cropping [45]. Wind erosion could be reduced when intercropped shorter crop with maize as maize acts as a wind barrier [22]. Besides, intercropping with legumes helps in controlling soil erosion as legumes act as a cover crop to reduce surface runoff [38]. Butternuts in corn-butternuts intercropping [28] and cowpea in maize-cowpea intercropping [50] act as cover crops to reduce runoff and soil erosion. Similarly, sorghum-cowpea intercropping has been reported to reduce runoff by 20–30% [5].

2.3.6. Promoting Soil Health and Enhancing Soil Fertility. Intercropping with legumes is commonly implemented as it can promote soil health and enhance soil fertility [17]. The presence of legumes in the intercropping system helps to fix atmospheric nitrogen into available nitrogen for uptake by crops through biological fixation [10] and reduce nitrogen losses in the soil [8]. Legumes are beneficial in supplying nitrogen to other crops; as a result, they can control the dependency of the crops on nitrogenous fertilizers [8, 51] and replace all or part of the nitrogen fertilization system [5]. Besides, crop residues from intercrops which remain in the field will decompose and enhance the organic matter build up in the soil for the next crops [12].

2.3.7. Crop Failure and Market Instability Insurance. Intercropping provides higher crop failure insurance compared to sole cropping [5]. In an intercropping system, by growing more than one crop, extreme weather such as drought, flood, and frost and pest and disease attacks might cause losses of a single crop; however, farmers may still harvest another component crop [10]. Besides, intercropping also provides insurance against unstable market [52]. According to Dwivedi et al. [10], small farmers are still able to benefit good prices from other component crops if the market price for a particular crop decreases.

3. Radiation Dynamics

3.1. Leaf Area Index (LAI). Leaf area index (LAI) functions as a key parameter of vegetation that explains the quantity of the leaf zone per unit of the horizontal ground area [53]. LAI can be defined as the proportion of the total projected leaf area per unit ground area [21]. LAI is a dimensionless quantity that characterizes an ecosystem canopy [54].

According to Addai and Alimiyawo [55], a higher LAI value would indicate greater photosynthetic activity that results in increased development and yield of the crop. Chakraborty et al. [56] also concluded that LAI tended to increase with PAR interception due to the increment in canopy volume. As LAI increased over time, it expanded until its peak value was reached and gradually decreased as a consequence of senescence of plant leaves [57]. Furthermore, Gezahen [58] claimed that crops displaying too small LAI could not have caught enough light, while too high LAI would lead to insufficient light in the lower leaves, therefore affecting the photosynthetic rate.

Intercropping between vegetables amaranths and radish had been reported to result in higher LAI in radish as vegetable amaranths had higher density [32]. In maize-soybean intercropping, significant effect on LAI was found in maize after increasing the plant density [59]. In terms of plotting system, intercropping plot system was found to have higher LAI compared to sole cropping plots [60].

3.2. Radiation Interception. The photosynthetically active radiation (PAR) is defined as the amount of light absorbed by the leaves to drive photosynthesis process [61] and convert the radiation into new biomass [62] called radiation use efficiency (RUE). According to Liu et al. [63], light interception is a major factor affecting plant photosynthesis which determines crop growth and yield [64].

The relationship between dry matter production and intercepted PAR is usually linear [65]. The fraction of the photosynthetically active radiation incident (Fi) is influenced by the canopy structure, which depends on the leaf area index (LAI) and crop geometry [19, 63]. As stated by Liu et al. [63], light distribution affects the photosynthesis rate in the crop canopy which influenced the crop productivity. Besides that, Chakraborty et al. [56] stated that the cumulative intercepted PAR depends on growth duration, canopy geometry, and plant morphology such as leaf area, angle, and orientation. According to Snow and White [66], the ratio of intercepted incident radiation rises as plant biomass and LAI rise until the LAI limit is reached (most intercepted radiation). Furthermore, the amount of light interception into the plant canopy was affected by several factors such as leaf area, leaf shape, leaf size, leaf surface, leaf thickness, and degree of dissection [65].

3.3. Radiation Use Efficiency. Radiation use efficiency (RUE) describes the slope of the relationship between total dry matter in regular harvesting and the respective cumulative intercepted radiation up to harvest time and is used to measure the efficiency of intercepted radiation of the crop in producing dry matter [67]. According to Bai et al. [68], RUE is largely controlled by the net photosynthetic capacity of the plant and by the structure of the canopy to some extent. In a certain growing period or whole growing season, RUE represents the crop's aggregated reaction to a number of variables affecting photosynthesis and respiration [69].

RUE was found to be higher in C4 species compared to C3 species, and nonlegumes of C3 species had higher RUE than legumes [70]. In some climatic conditions, RUE may also vary within the same species, such as maize in warm regions has higher RUE compared to maize grown in cooler regions [71]. In intercropping cases, C3 crops are usually found to have higher RUE due to their tall height which is slightly lower than C4 plants. Having exposed towards high light intensity makes C4 plants utilize their potential for high photosynthetic rates, while C3 plants are vice versa [69]. In a previous study, RUE of groundnut from C3 short species was found to increase by 46% after been intercropped with C4 tall species millet [72]. According to Liu et al. [39], RUE of intercrops was associated with a variety of variables including crop genotype, leaf photosynthetic capacity, agronomic practices, pest and disease incidence, precipitation, soil water, and nutrition.

3.4. Canopy Characteristics. Canopy characteristics including leaf area index (LAI) are a significant element in optimizing the structure of crop canopy that can enhance photosynthetic productivity of the canopy and thus enhance future crop yield [73]. According to Liu et al. [63], plant canopy affects the fraction of the photosynthetically active radiation incident (Fi) intercepted by crops. Martini [65] stated that the quantity of light interception by the canopy relies on the LAI and the canopy characteristics. The angle of the leaf determines the penetration of PAR into the canopy of the crop. The crop growth and development [74] and overall photosynthesis and yield performance [75] were influenced by the amount of light intercepted into the crop canopy which was dependent on leaf characteristics such as thickness, surface, size, shape, and the degree of dissection [21].

According to Hue et al. [76] and Bhattacharya [77], the leaf surface and leaf area increase as light interception increases into the crop canopy. Light interception differences were observed between erectophilic (mostly erect) and planophilic (mostly horizontal) leaves [78, 79]. The effectiveness of interception light was higher on wide, bigger, and planophilic leaves than on narrow, small, and erectophilic leaves [77, 80]. According to Lowry and Smith [81], more horizontal or planophilic leaves would cause more light to hit the surface of the leaf and boost the effectiveness of light interception.

For example, legume crops such as soybean have horizontal and planophile-type leaves [82]. This type of leaves has smaller leaf size and lower leaf area [39] which tend to intercept less light [83]. Meanwhile, cereal crops such as corn had erectophile leaf and bigger leaf area [57] which tended to intercept more radiation for photosynthesis process that led to high yield [84], thus resulting in greater radiation use efficiency (RUE) [78].

3.5. Effects of Radiation Dynamics on Crop Growth Performance and Yield in the Intercropping System. Crop productivity relies primarily on the amount of radiation intercepted by the plants if other factors, such as water, nutrients, disease, and weeds, are not restricted [85]. Du et al. [86] emphasized that light has a significant role in primary net productivity, and the accessibility of light is connected with the canopy structure and plant characteristics [87]. Besides, Tao et al. [87] stated that intercepted photosynthetically active radiation (IPAR) and radiation use efficiency (RUE) influenced the growth and development of crops. According to Niinemets [88], light interception reduces exponentially from the top to the bottom of the canopy, and the leaf net photosynthetic rate (Pn) rises gradually from the bottom to the top of the canopy. Meanwhile, Onoda et al. [89] claimed that the light interception by taller plants is more effective per unit of surface biomass compared to shorter plants. The statement was supported by Kiseve [38] who stated that, in an intercropping system, light interception was dominated by the taller plants at the upper layer, while the light transmitted to the ground was utilized by the shorter plants.

Generally, the PAR and RUE intercepted by crops differed in various intercropping configurations [39]. With the impact of mixing distinct spatiotemporal use of radiation between component plants in the scheme, intercropping has higher potential for radiation capture and use compared to sole cropping [85]. Intercropping showed higher intercepted PAR and RUE than sole cropping. High intercepted PAR resulted in high productivity of intercropped crops ([90], [91]). According to Yulong et al. [92], growth rates of the intercrops were proportional to the amount of PAR intercepted. Besides, according to Tao et al. [87], low productivity was often caused by low RUE.

The use of captured solar radiation in smaller and shadier legumes in legume-based intercropping is more effective compared to sole crops [16]. For example, in observation-based research conducted by Liu et al. [39] and Nur Arina [21], their findings suggested that soybean with lower leaf size has low LAI, which in turn would result in reduced light interception and low productivity in sole cropping compared to the intercropping system. Besides, their previous studies showed that the short statured soybean in the intercropping system gave higher RUE value than sole cropping due to the increased diffused light and lower light saturation in the system.

Furthermore, Liu et al. [57] concluded that, in cereal intercrops, taller cereal crops with better canopy structure were found to have better solar radiation interception than the sole crop. Mohsen Abadi and Jahansooz [93] and Karimian et al. [94] showed the effectiveness of radiation use in the intercropping of wheat and canola was greater than that of sole cropping because of the immediate association between canopy closing speed and radiation use in the system. Lindquist et al. [95] proposed that loss of radiation could be reduced with better soil cover in intercropping, resulting in an increase in the absorption value of total radiation, rather than sole cropping that would result in increased radiation use efficiency and crop yield performance [94]. Besides, due to the greater light interception within the canopy, plants with erect leaves showed significant yield benefit over those with horizontal leaves [63, 96].

4. Conclusion

As a general conclusion, intercropping is practiced globally and could contribute to long-term food stability. In order to feed the growing world population, intercropping is one of the alternatives in enhancing food production. Radiation dynamics including leaf area index, canopy characteristics, photosynthetically active radiation, and radiation use efficiency are the main aspects in maximizing yield as well as total productivity of both crops. Besides, although there is greater productivity in all intercrops, it is better for the farmers to select compatible crops in intercropping systems as each crop differs in radiation dynamics, growth habits, and productivity.

Conflicts of Interest

The authors declare no conflicts of interest.

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References

[1] K. M. Fung, A. P. K. Tai, T. Yong, X. Liu, and H. M. Lam, "Co-benefits of intercropping as a sustainable farming method for safeguarding both food security and air quality," *Environmental Research Letters*, vol. 14, pp. 1–12, 2019.

[2] M. Raseduzzaman, *Intercropping for Enhanced Yield Stability and Food Security*, Master's Thesis, Swedish University of Agricultural Sciences, Uppsala, Sweden, 2016.

[3] M. A. Altieri and C. A. Nicholls, "Agroecological foundation for pest management in the tropics: learning from traditional farmers," in *Integrated Pest Management In Tropical Regions*, C. Rapisarda and G. E. M. Cocuzza, Eds., pp. 6–17, CABI, Wallingford, UK, 2017.

[4] M. A. Altieri, "The ecological role of biodiversity in agro-ecosystems," *Agriculture, Ecosystems & Environment*, vol. 74, no. 1-3, pp. 19–31, 1999.

[5] A. Lithourgidis, C. Dordas, C. Damalas, and D. Vlachostergios, "Annual intercrops: an alternative pathway for sustainable agriculture," *Australian Journal of Crop Science*, vol. 5, pp. 396–410, 2011.

[6] J. G. Joak, "Working with farmers in upper nile state, South Sudan for farmers to adopt multi-cropping practice in nakdiar and doleep payams," Master's Thesis, Høgskolen I Oslo Og Akershus, Oslo, Norway, 2012.

[7] E. M. Musa, E. A. Elsheikh, I. A. Mohamed Ahmed, and E. E. Babiker, "Intercropping sorghum (*Sorghum bicolor* L.) and cowpea (*Vigna unguiculata* L.)," *Effect of Bradyrhizobium Inoculation and Fertilization on Minerals Composition of Sorghum Seeds*, ISRN Agronomy, New York, NY, USA, 2011.

[8] N. Iqbal, S. Hussain, Z. Ahmed et al., "Comparative analysis of maize-soybean strip intercropping systems: a review," *Plant Production Science*, vol. 22, no. 2, pp. 131–142, 2019.

[9] H. Eskandari, "Intercropping of wheat (*Triticum aestivum* L.) and bean (*Vicia faba*): effects of complementarity and competition of intercrop components in resource consumption on dry matter production and weed growth," *African Journal of Biotechnology*, vol. 10, pp. 17755–17762, 2011.

[10] A. Dwivedi, I. Dev, V. Kumar et al., "Potential role of maize-legume intercropping systems to improve soil fertility status under smallholder farming systems for sustainable agriculture in India," *International Journal of Life Sciences Biotechnology and Pharma Research*, vol. 4, no. 3, pp. 145–157, 2015.

[11] J. A. Idoko, T. Iorlamen, and A. E. Offordile, "Effect of intercropping some crop species with orange flesh sweet potato on the performance of orange flesh sweet potato varieties in Makurdi," *International Journal of Agricultural Policy and Research*, vol. 6, no. 3, pp. 28–37, 2018.

[12] H. Gebru, "A review on the comparative advantages of intercropping to monocropping system," *Journal of Biology, Agriculture and Healthcare*, vol. 5, no. 9, pp. 1–13, 2015.

[13] X. Dai, L. Pu, and F. Rao, "Assessing the effect of a crop-tree intercropping program on smallholders' incomes in rural xinjiang, China," *Sustainability*, vol. 9, no. 9, p. 1542, 2017.

[14] Z. G. Wang, X. Jin, X. G. Bao et al., "Intercropping enhances productivity and maintains the most soil fertility properties relative to sole cropping," *PLoS One*, vol. 9, no. 12, pp. 1–24, 2014.

[15] O. N. Adeniyan, O. A. Aluko, S. O. Olanipekun, J. O. Olasoji, and V. O. Aduramigba-Modupe, "Growth and yield performance of cassava and maize intercrop under different plant population density of maize," *Journal of Agricultural Science*, vol. 6, no. 8, pp. 35–40, 2014.

[16] R. W. Brooker, A. E. Bennett, W. F. Cong et al., "Intercropping: a synthesis of research in agronomy, plant physiology and ecology," *New Phytologist*, vol. 206, no. 1, pp. 107–117.

[17] K. Jones and M. Ryan, "Advancing intercropping research and practices in industrialized agricultural landscapes," *Agriculture*, vol. 8, no. 6, p. 80, 2018.

[18] C. A. Petrie and J. Bates, "'Multi-cropping', intercropping and adaptation to variable environments in indus south asia," *Journal of World Prehistory*, vol. 30, no. 2, pp. 81–130, 2017.

[19] L. Z. Zhang, J. H. J. Spiertz, S. P. Zhang, B. Li, and W. Van der Werf, "Nitrogen economy in relay intercropping systems of wheat and cotton," *Plant and Soil*, vol. 303, no. 1-2, pp. 55–68, 2008.

[20] H. Mohd Anim, *Penutup Bumi – Teknik Menanam*, 2014, http://animhosnan.blogspot.com/2014/06/penutup-bumi-teknik-menanam.html.

[21] I. Nur Arina, "Growth performance, yield and quality of sweet potato (*Ipomoea batatas* (L.) Lam) in response to different cropping systems," Master's thesis, Universiti Putra Malaysia, Seri Kembangan, Malaysia, 2019.

[22] T. H. Seran and I. Brintha, "Review on maize based intercropping," *Journal of Agronomy*, vol. 9, no. 3, pp. 135–145, 2010.

[23] L. P. Yadav, S. K. Malhotra, and A. V. T. A. R. Singh, "Effect of intercropping, crop geometry and organic manures on growth and yield of broccoli (*Brassica oleracea var italica*)," *Indian Journal of Agriculture Science*, vol. 87, pp. 318–324, 2017.

[24] A. Punyalue, S. Jamjod, and B. Rerkasem, "Intercropping maize with legumes for sustainable highland maize production," *Mountain Research and Development*, vol. 38, no. 1, pp. 35–44, 2018.

[25] J. M. M. Matusso, J. N. Mugwe, and M. Mucheru-Muna, "Effect of different maize (*Zea mays* L.) – soybean (*Glycine max* (L.) Merrill) intercropping patterns on yields, light interception and leaf area index in Embu West and Tigania East sub counties abstract," *Academic Research Journal of Agricultural Science and Research*, vol. 2, pp. 6–21, 2014.

[26] M. O. Ijoyah and J. Jimba, "Evaluation of yield and yield components of Maize (*Zea mays* L.) and okra (*Abelmoschus esculentus* L. Moench) intercropping system at Makurdi, Nigeria," *Journal of Biodiversity and Environmental Sciences*, vol. 2, no. 2, pp. 38–44, 2012.

[27] T. Amede and Y. Nigatu, "Interaction of components of sweetpotato-maize intercropping. under the semi-arid conditions of the rift valley, Ethopia," *Journal of Tropical Agriculture*, vol. 78, pp. 1–7, 2001.

[28] S. Muperi, *Effects of Intercropping Maize (Zea mays) with Butternuts (Cucurbita Moschata) at Varying Butternut Population Levels on Maize Growth, Yield and Weed Suppression*, Bachelor Thesis, Midlands State University, Gweru, Zimbabwe, 2016.

[29] A. A. Isaac, *Response of cowpea/maize intercropping system to varying component population ratios using different intercropping efficiency indices*, PhD Thesis, University of Ilorin, Ilorin, Nigeria, 2011.

[30] M. H. Maluleke, A. Addo-Bediako, and K. K. Ayisi, "Influence of maize/lablab intercropping on lepidopterous stem borer infestation in maize," *Journal of Economic Entomology*, vol. 98, no. 2, pp. 384–388, 2005.

[31] C. O. Muoneka and J. E. Asiegbu, "Effect of okra planting and spatial arrangement in intercrop with maize on the growth and yield component species," *Journal of Agronomy and Crop Science*, vol. 179, pp. 201–207, 1997.

[32] I. Brintha and T. H. Seran, "Effect of paired row planting of radish (*Raphanus sativus* L.) intercropped with vegetable amaranthus (*Amaranthus tricolor* L.) on yield components of

radish in sandy regosol," *Journal of Agriculture Sciences*, vol. 4, pp. 19–28, 2009.

[33] F. O. Takim, "Advantages of maize-cowpea intercropping over sole cropping through competition indices," *Journal of Agriculture and Biodiversity Research*, vol. 1, no. 4, pp. 53–59, 2012.

[34] H. Hauggaard-Nielsen and E. S. Jensen, "Facilitative root interactions in intercrops," *Plant Ecophysiology*, vol. 274, no. 1-2, pp. 237–250, 2005a.

[35] J. Jalilian, A. Najafabadi, and M. R. Zardashti, "Intercropping patterns and different farming systems affect the yield and yield components of safflower and bitter vetch," *Journal of Plant Interactions*, vol. 12, no. 1, pp. 92–99, 2017.

[36] U. L. Undie, D. F. Uwah, and E. E. Attoe, "Effect of intercropping and crop arrangement on yield and productivity of late season maize-soybean mixtures in the humid environment of South Southern Nigeria," *Journal of Agricultural Science*, vol. 4, no. 4, pp. 37–50, 2012.

[37] S. A. Ennin, M. D. Clegg, and C. A. Francis, "Resource utilization in soybean/maize intercrops," *African Crop Science Journal*, vol. 10, no. 3, pp. 251–261, 2002.

[38] S. M. Kiseve, *Evaluation of Legume Cover Crops Intercropped with Coffee*, Master Thesis, University of Nairobi, Nairobi, Kenya, 2012.

[39] X. Liu, T. Rahman, F. Yang et al., "PAR interception and utilization in different maize and soybean intercropping patterns," *PLoS One*, vol. 12, no. 1, pp. 1–17, 2017.

[40] A. Ghanbari, M. Dahmardeh, B. A. Siahsar, and M. Ramroudi, "Effect of maize (*Zea mays* L.) and cowpea (*Vigna unguiculata* L.) intercropping on light distribution, soil temperature and soil moisture in arid environment," *Journal of Food, Agriculture and Environment*, vol. 8, no. 1, pp. 102–108, 2010.

[41] W. H. Alla, E. M. Shalaby, R. A. Dawood, and A. A. Zohry, "Effect of cowpea (Vigna sinensis L.) with maize (Zea mays L.) intercropping on yield and its components," *International Scholarly and Scientific Research & Innovation*, vol. 8, no. 11, pp. 1258–1264, 2014.

[42] Y. B. Bantie, "Determination of effective spatial arrangement for intercropping of maize (*Zea mays* L.) and potato (*Solanum tuberosum* L.) using competition indices Ethiopia," *Journal of Horticulture*, vol. 2, no. 137, pp. 1–7, 2015.

[43] S. A. A. Mohammed, "Assessing the land equivalent ratio (LER) of two leguminous pastures (*clitoria* and *siratro*) intercropping at various cultural practices and fencing at zalingei, western darfur state, Sudan," *ARPN Journal of Science and Technology*, vol. 2, pp. 1074–1080, 2012.

[44] S. P. Yadav and Y. Sonia, "Feasibility of sugarcane based intercropping systems for subtropical India," *Plant Archives*, vol. 17, no. 2, pp. 1297–1300, 2017.

[45] M. Aziz, A. Mahmood, M. Asif, and A. Ali, "Wheat-based intercropping: a review," *J Anim Plant Science*, vol. 25, pp. 896–907, 2015.

[46] R. Kumar, A. B. Turkhede, R. K. Nagar, and A. Nath, "Effect of different intercrops on growth and yield attributes of American cotton under dry land condition," *International Journal of Current Microbiology and Applied Sciences*, vol. 6, no. 4, pp. 754–761, 2017.

[47] K. Jabran, G. Mahajan, V. Sardana, and B. S. Chauhan, "Allelopathy for weed control in agricultural systems," *Crop Protection*, vol. 72, pp. 57–65, 2015.

[48] A. K. Kumar, M. Reddy, A. Sivasankar, and N. Reddy, "Yield and economics of maize (*Zea mays*) and soybean (*Glycine max*) in intercropping under different row proportions," *Indian Journal of Agricultural Science*, vol. 73, pp. 69–71, 2003.

[49] S. Samanta, S. Kumar, R. S. Khedwal, and S. R. Jakhar, "Allelopathy for sustainable weed management," *Journal of Pharmacognosy and Phytochemistry*, vol. SP1, pp. 832–837, 2017.

[50] N. K. Sharma, R. J. Singh, D. Mandal, A. Kumar, N. M. Alam, and S. Keesstra, "Increasing farmer's income and reducing soil erosion using intercropping in rainfed maize-wheat rotation of Himalaya, India," *Agriculture, Ecosystems & Environment*, vol. 247, pp. 43–53, 2017.

[51] A. Regehr, M. Oelbermann, C. Videla, and L. Echarte, "Gross nitrogen mineralization and immobilization in temperate maize-soybean intercrops," *Plant and Soil*, vol. 391, no. 1-2, pp. 353–365, 2015.

[52] B. Lulie, "Intercropping practice as an alternative pathway for sustainable agriculture: a review," *Academic Research Journal of Agricultural Science and Research*, vol. 5, no. 6, pp. 440–452, 2017.

[53] G. Yan, R. Hu, J. Luo et al., "Review of indirect optical measurements of leaf area index: recent advances, challenges, and perspectives," *Agricultural and Forest Meteorology*, vol. 265, pp. 390–411, 2019.

[54] N. J. J. Breda, "Ground-based measurements of leaf area index: a review of methods, instruments and current controversies," *Journal of Experimental Botany*, vol. 54, no. 392, pp. 2403–2417, 2003.

[55] I. K. Addai and M. Alimiyawo, "Graphical determination of leaf area index and its relationship with growth and yield parameters of Sorghum (*Sorghum bicolor* L. Moench) as affected by fertilizer application," *Journal of Agronomy*, vol. 14, no. 4, pp. 272–278, 2015.

[56] P. K. Chakraborty, S. Banerjee, S. Banerjee, A. Mukherjee, and R. Nath, "Extinction coefficient and photosynthetically active radiation use efficiency of summer rice as influenced by transplanting dates," *Journal of Environmental Biology*, vol. 39, no. 4, pp. 467–471.

[57] T. Liu, F. Song, S. Liu, and X. Zhu, "Light interception and radiation use efficiency response to narrow-wide row planting patterns in maize," *Australian Journal of Crop Science*, vol. 6, no. 3, pp. 506–513, 2012.

[58] A. M. Gezahen, *Integrated nutrient management for maize-soybean cropping system*, PhD Thesis, Universiti Putra Malaysia, Seri Kembangan, Malaysia, 2016.

[59] R. B. Prasad and R. M. Brook, "Effect of varying maize densities on intercropped maize and soybean in Nepal," *Experimental Agriculture*, vol. 41, no. 3, pp. 365–382, 2005.

[60] B. Dimitrios, P. Panayiota, K. Aristidis, P. Sotiria, K. Anestis, and E. Aspasia, "Weed-suppressive effects of maize-legume intercropping in organic farming," *International Journal of Pest Management*, vol. 56, no. 2, pp. 173–181, 2009.

[61] A. Koocheki, M. P. Rezvani, and H. R Fallahi, "Effects of planting dates, irrigation management and cover crops on growth and yield of saffron (Crocus sativus L.)," *Quarterly Agroecology Journal*, vol. 8, no. 3, pp. 435–451, 2016.

[62] H. Miranzadeh, Y. Emam, H. Seyyed, and S. Zare, "Productivity and radiation use efficiency of four dryland wheat cultivars under different levels of nitrogen and chlormequat chloride," *Journal of Agricultural Science and Technology*, vol. 13, pp. 339–351, 2011.

[63] T. Liu, F. Song, S. Liu, and X. Zhu, "Canopy structure, light interception, and photosynthetic characteristics under different narrow-wide planting patterns in maize at silking stage," *Spanish Journal of Agricultural Research*, vol. 9, no. 4, pp. 1249–1261, 2011.

[64] G. Ouma and P. Jeruto, "Sustainable horticultural crop production through intercropping: The case of fruits and

vegetable crops: A review," *Agriculture and Biology Journal of North America*, vol. 1, no. 5, pp. 1098–1105, 2010.

[65] M. Y. Martini, *Physiological and Environmental Constraints to Winter Forage Crops Production*, PhD Thesis, Lincoln University, Lincoln, New Zealand, 2012.

[66] V. O. Snow and T. A. White, "Process-based modelling to understand which ryegrass characteristics can increase production and decrease leaching in grazed grass-legume pastures," *Crop and Pasture Science*, vol. 64, no. 3, pp. 265–284, 2013.

[67] T. R. Sinclair and R. C. Muchow, "Radiation use efficiency," *Advance Agronomy*, vol. 65, pp. 5–265, 1999.

[68] Z. Bai, S. Mao, Y. Han et al., "Study on light interception and biomass production of different cotton cultivars," *PLoS One*, vol. 11, no. 5, pp. 1–17, 2016.

[69] G. Fang, K. V. I. Martin, S. Elisabeth et al., "Intercropping wheat and maize increases total radiation interception and wheat RUE but lowers maize RUE," *European Journal of Agronomy*, vol. 84, pp. 125–139, 2017.

[70] G. Gosse, C. Varlet-Grancher, R. Bonhomme, M. Chartier, J.-M. Allirand, and G. Lemaire, "Production maximale de matière sèche et rayonnement solaire intercepté par un couvert végétal," *Agronomie*, vol. 6, no. 1, pp. 47–56, 1986.

[71] F. H. Andrade, S. A. Uhart, and A. Cirilo, "Temperature affects radiation use efficiency in maize," *Field Crops Research*, vol. 32, no. 1-2, pp. 17–25, 1993.

[72] B. Marshall and R. W. Willey, "Radiation interception and growth in an intercrop of pearl millet/groundnut," *Field Crops Research*, vol. 7, pp. 141–160, 1983.

[73] G. Feng, H. Luo, Y. Zhang et al., "Relationship between plant canopy characteristics and photosynthetic productivity in diverse cultivars of cotton (*Gossypium hirsutum* L.)," *The Crop Journal*, vol. 4, no. 6, pp. 499–508, 2016.

[74] S. Sankula, M. J. VanGessel, and R. R. Mulford, "Corn leaf architecture as a tool for weed management in two corn production systems," *Weed Science*, vol. 52, no. 6, pp. 1026–1033, 2004.

[75] S. Huang, Y. Gao, Y. Li, L. Xu, H. Tao, and P. Wang, "Influence of plant architecture on maize physiology and yield in the Heilonggang River valley," *The Crop Journal*, vol. 5, no. 1, pp. 52–62, 2017.

[76] S. M. Hue, S. Chandran, and A. N. Boyce, "Variations of leaf and storage roots morphology in *Ipomoea batatas* L. (sweet potato) cultivars," *Acta Horticulturae*, vol. 943, pp. 73–79, 2010.

[77] A. Bhattacharya, "Radiation-use efficiency under different climatic conditions," in *Changing Climate and Resource Use Efficiency in Plants*, pp. 65-66, Academic Press, Cambridge, MA, USA, 2018.

[78] A. Merry, T. B. Acuna, P. Riffkin, and R. Richards, "Can leaf architecture improve crop biomass and yield in wheat?" in *Proceedings of the 18th Australian Agronomy Conference 2017*, Ballarat, Victoria, Australia, September 2017.

[79] M. Vincini, F. Calegari, and R. Casa, "Sensitivity of leaf chlorophyll empirical estimators obtained at Sentinel-2 spectral resolution for different canopy structures," *Precision Agriculture*, vol. 17, no. 3, pp. 313–331, 2015.

[80] L. T. Mannetje, "Advances in grassland science," *NJAS-wageningen Journal of Life Sciences*, vol. 50, no. 2, pp. 195–221, 2003.

[81] C. J. Lowry and R. G. Smith, "Weed control through crop plant manipulations," in *Non-Chemical Weed Control*, K. Jabran and B. S. Chauhan, Eds., pp. 61–71, Academic Press, Cambridge, MA, USA, 2018.

[82] B. L. Blad and D. G. Baker, "Orientation and distribution of leaves within soybean canopies 1," *Agronomy Journal*, vol. 64, no. 1, pp. 26–29, 1972.

[83] P. Grassini, J. E. Specht, M. Tollenaar, I. Ciampitti, and K. G. Cassman, "Crop physiology," in *High-yield Maize–Soybean Cropping Systems in the US Corn Belt*, pp. 17–41, Academic Press, Cambridge, MA, USA, 2015.

[84] C. Li, Y. Li, Y. Shi et al., "Genetic control of the leaf angle and leaf orientation value as revealed by ultra-high density maps in three connected maize populations," *PLoS One*, vol. 10, no. 3, pp. 1–13, 2015.

[85] M. Tsubo, S. Walker, and H. O. Ogindo, "A simulation model of cereal-legume intercropping systems for semi-arid regions," *Field Crops Research*, vol. 93, no. 1, pp. 10–22, 2005.

[86] X. Du, Q. Li, T. Dong, and K. Jia, "Winter wheat biomass estimation using high temporal and spatial resolution satellite data combined with a light use efficiency model," *Geocarto International*, vol. 30, no. 3, pp. 258–269, 2015.

[87] Z.-q. Tao, D.-m. Wang, S.-k. Ma, Y.-s. Yang, G.-c. Zhao, and X.-h. Chang, "Light interception and radiation use efficiency response to tridimensional uniform sowing in winter wheat," *Journal of Integrative Agriculture*, vol. 17, no. 3, pp. 566–578, 2018.

[88] Ü. Niinemets, "Photosynthesis and resource distribution through plant canopies," *Plant, Cell & Environment*, vol. 30, no. 9, pp. 1052–1071, 2007.

[89] Y. Onoda, J. B. Saluñga, K. Akutsu, S.-i. Aiba, T. Yahara, and N. P. R. Anten, "Trade-off between light interception efficiency and light use efficiency: implications for species coexistence in one-sided light competition," *Journal of Ecology*, vol. 102, no. 1, pp. 167–175, 2014.

[90] E. N. Masvaya, J. Nyamangara, K. Descheemaeker, and K. E. Giller, "Is maize-cowpea intercropping a viable option for smallholder farms in the risky environments of semi-arid southern Africa?" *Field Crops Research*, vol. 209, pp. 73–87, 2017.

[91] M. Rezig, A. Sahli, M. Hachicha, F. B. Jeddi, and Y. Harbaoui, "Potato (*Solanum tuberosum* L.) and bean *(Phaseolus vulgaris* L.) in sole intercropping: effects on light interception and radiation use efficiency," *Journal of Agricultural*, vol. 5, no. 9, pp. 65–77, 2013.

[92] L. U. O. Yulong, W. U. Xueli, T. A. N. G. Daobin et al., "Effect of maize (*Zea mays* L.) plant-type on yield and photosynthetic characters of sweet potato (*Ipomoea balatas* L.) in intercropping system," *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*, vol. 45, no. 1, pp. 245–254, 2017.

[93] G. H. Mohsen Abadi and M. R. Jahansooz, "Evaluation of the effectiveness and radiation use efficiency in intercropping of barley (*Hordeum vulgare*) and vetch (*Dasycarpa vicia villosa ssp.) at different levels of nitrogen*," *Iranian Journal of Crop Sciences*, vol. 3, pp. 419–427, 2013.

[94] K. Karimian, R. Ghorbani, A.-R. Koochaki, and G.-A. Asadi, "Investigating of radiation absorption and use efficiency in intercropping of wheat and canola," *International Journal of Life Sciences*, vol. 9, no. 6, pp. 61–71, 2015.

[95] J. L. Lindquist, T. J. Arkebauer, D. T. Walters, K. G. Cassman, and A. Dobermann, "Maize radiation use efficiency under optimal growth conditions," *Agronomy Journal*, vol. 97, no. 1, pp. 72–78, 2005.

[96] D. I. Dickmann, D. A. Michael, J. G. Isebrands, and S. Westin, "Effects of leaf display on light interception and apparent photosynthesis in two contrastingPopuluscultivars during their second growing season," *Tree Physiology*, vol. 7, no. 1-4, pp. 7–20, 1990.