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Review

Exploring the Potential of Using Fertilizers to Condition the Metabolism and Physiology of Dual-Yield Crops in a Water Deficit Environment: A Review

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Abstract: Research on the production of field crops in semi-arid regions mainly focuses on irrigation and climate change adaptation because these are emphasized as the practices determining yields of field crops in these regions. The need to evolve research in this direction is important because general crop production systems in all regions can adopt the findings from this kind of research during unforeseen drought conditions. Research on fertilizers is usually treated as a secondary factor or neglected despite it being an important practice for crops growing in semi-arid regions. Fertilization affects parameters that are responsible for metabolism, physiology, morphology, and subsequent crop yields under drought conditions. This literature review focused on dual-yield crops' response to fertilization and the potential for researchers to employ these responses for the improvement of cultivations and yields in semi-arid regions. These findings indicated that the application of various nitrogen (N), phosphorus (P), or potassium (K) fertilizers is common and based on broadcasting and banding techniques. The split application of N, P, and K fertilizers is mostly employed to adjust the metabolism, physiology, and morphology of crops at different growth stages so that the crops can be exposed to water shortages. These adjustments can be used to increase or decrease the water use efficiency of the crops, which is highly associated with biological and economic yields. Research on micro-elements in dual-yield crops is currently very limited. Multidimensional future research based on the effects of micro-elements on the metabolism, physiology, and morphology of dual-yield crops is recommended. This research must be conducted with the aim of enhancing water use efficiency.

Keywords: African yam bean; *Cucurbita pepo*; biological yield; *Sorghum bicolor*; water use efficiency

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1. Introduction

Food security is challenged by gradual population growth in the developing world [1]. The current crop production systems and associated research normally focus on sole crops that produce a single yield as food in the form of fruit, leaves, starch, or proteins. This practice can be improved or combined with other methods such as crop rotation and intercropping to meet the food needs of the burgeoning population. It is estimated that food production should be doubled to meet the food security demands of the global population in 2050 [2]. Extending the sole yield crop production will require the wide destruction of the environment, a reduction in land used for non-consumed crops like fiber, and the consumption of non-food organisms as food. The need for increased food sources will compel producers to ignore or neglect common obligations and ethics associated with the production of consumable products [3].

There are many crops that produce two food types (dual-yield) per plant that are commercially neglected and not optimally researched. These include African yam beans

(*Sphenostylis stenocarpa*), which produce leguminous seeds and starch-rich tubers [4]; pumpkins (*Cucurbita pepo*), which produce edible vines and a delicious nutrition-rich squash fruit that contains seeds that are processed into snacks [5]; and sorghum (*Sorghum bicolor*), which produces cereal grains, while its stem can be crushed to extract sweetening syrup [6].

Increasing the production of dual-yield crops will enable producers to double the yields obtainable in a unit area. This dual-yield production is vital in areas of water shortages because every amount of water used for irrigation must have an optimum biological yield output. The farming of dual-yield crops in semi-arid regions is usually complicated by irrigation and fertilization scheduling, which need to be accommodative of more than one consumed product. These dual-yield crops must be ideally cultivated in such a way that each product meets quality levels that are competitive with the crops that have a single yield. Otherwise, they will not be purchasable by consumers in the market. Consumers that do not grow their own food are not interested in either food production or the maintenance of food security; they buy what is available to them. Most consumers are not even aware of the current issues facing farmers, such as increasing the productivity in a unit land area [7], global population growth [8,9], and environmentally sustainable crop production systems [10].

Crops cultivated to produce only grains or fruits normally reduce vegetative growth and increase seed development under drought conditions. Through this morphological change, the sole yield is affected less than it would be if a crop had to partition its energy to both vegetative and reproductive development, simultaneously, like in dual-yield crops. There is limited research on the irrigation and fertilization of dual-yield crops. The unique cultivation challenge in scheduling the fertilization of dual-yield crops in a water deficit environment is their need to continue growing vegetatively when they have reached the seed development stage. Complications in scheduling fertilizer applications on dual-yield crops are usually caused by the need for different nutrients at different periods before the harvest of all the parts (regarded as the yield). For example, the African yam bean (AYB) seeds meant for consumption reach harvest maturity before the roots have grown into tubers. At the stage of seed harvest, the seeds need low-nitrogen (N) fertilizer while the roots need high-N fertilizer to grow to an acceptable tuber size. Increasing the N application at this stage will lead to the unwanted further hardening of seeds, resulting in difficulties pertaining to their cookability [11]. Research exploring the effects of the nutrients available for plant uptake when generating dual-yield is needed. Fertilization affects parameters that are responsible for processes such as metabolism, physiology, and morphology, which can be altered to improve dual-yield developments under drought conditions. This review focuses on the effects of fertilization on the metabolism, physiology, and adaptation of crops that produce two consumable parts in water deficit regions. The main objective is to expatiate on the literature on synchronizing fertilizer application with physio-metabolic reactions and phenological changes, and on the yield of crops in drought-threatened regions.

2. Common Fertilization of Dual-Yield Field Crops and Their Effect on Drought Tolerance and Yield

2.1. Nitrogen (N)

Nitrogen is an important nutrient in the vegetative growth and development of all plants. Its application time on dual-yield crops is very important as it determines whether the plant partitions towards vegetative growth or the development of new reproductive structures. The source of N for most producers and researchers is a fertilizer that provides N in the form of organic matter: NO_3^- or NH_4^+. Various studies have used N to improve the biological yield, which results in increased development of reproductive structures and economic yield. Warisman et al. [12] found that N application in zucchini plants significantly improved overall yield by enhancing parameters including plant length, number of leaves, leaf area, fresh weight, dry weight, number of fruits, and fruit weight. These improvements can be associated with improved morphological and physiological traits that improve the

metabolism of assimilates during the yielding stage of plants. Shehab and Guo [13] found that application of N fertilizer on sweet sorghum increases photosynthetic rate, stomatal conductance, and transpiration rate. These changes, observed after N application, can be associated with drought tolerance by relating the physiology and morphology of the crop to the metabolism of inherent plant growth regulators. Shehab and Guo [13] discovered an increase in proline, soluble protein, hydrocyanic acid, superoxide dismutase, peroxidase, catalase, and polyphenol peroxidase, which are amongst the important secondary phytochemicals associated with the water use efficiency of plants.

Nitrogen is commonly applied in split applications, depending on the experimental site preparation. For instance, Meena et al. [14] used a 50:50 split application with half applied before sowing and the remaining half as a top dressing 30 days after planting sorghum. The total N applied was 36.8 kg/ha, which is close to the recommended amount for sorghum. Split application is normally carried out on field experiments but is not mandatory in pot experiments. Lestari et al. [15] successfully applied 11.25 g/plant N using 1:1:1 NPK fertilizer as a top dressing prior to sowing sorghum seedlings in a pot trial. However, splitting is not necessary on crops with short seasons, such as amaranths. Akamine et al. [16] successfully used the discing-in technique prior to sowing to apply 50 g/m^2 of N on amaranths. Splitting ensures even N distribution throughout the growing and yielding season. Chemical fertilizers are readily available for plant uptake but have a limited availability span. Some studies use organic fertilizers such as livestock manure, which releases N slowly and extends coverage throughout the season. Manure application is usually not split, but some researchers split it to elongate the N release period. de Souza et al. [17] used split application of 45 kg/ha cattle manure at planting, using discing-in and a top dressing at 25 days after planting zucchini. Split applications can mitigate the effects of water shortages in semi-arid regions because the N available would be adequate for growth but not excessive. Excessive N available during water shortages leads to toxicity that drastically reduces growth and the development of yield in dual-yield crops.

2.2. Phosphorus (P)

Phosphorus is a constituent of plant cells responsible for cellular activities that fuel mitosis in the growing tips of plants. Its application and availability significantly affect plant metabolism. The source of phosphorus for most studies is superphosphate, which contains P as 46% P_2O_5. Ikhajiagbe et al. [18] found that the African yam bean grain yield showed a diminishing return from 1509.02 kg grain/ha to 1420.72 kg grain/ha when phosphate fertilization increased from 330 kg/ha to 550 kg/ha. Superphosphate was applied three weeks after planting (WAP) through a banding method [18]. Although phosphorus is an immobile nutrient in the soil, its application timing, amount, and technique depend on the nature of the dual-yield crop. Raman et al. [19] and Akamine et al. [16] reported success in the pre-sowing application of 250 kg/ha DAP and 50 g/m^2 P on amaranths. This application is effective on dual-yield crops with a short season, but some dual-yield crops need an extended season, which compromises phosphorus availability. Warrisman et al. [12] used split applications for the top dressing of zucchini plants at 7 and 21 days after planting. P fertilizer was applied using a top dressing at 5 cm from the plant stems. This technique reduced the possibility of the contact toxicity that can result from P fertilizers like phosphates. Applying manures in the first application and adding P later during the growing season can also reduce the possibility of toxicity. de Souza et al. [17] applied cattle manure at planting and added 69 kg/ha P 40 days after planting zucchini.

However, application of P during growth stages restricts its availability to crops since it is an immobile nutrient in the soil. Some studies have developed fertilization methods that provide certain enzymes or catalysts to augment the P release from the fertilizer and its availability for plant uptake. Yam bean (*Pachyrhizus erosus* L. Urban) had a higher shoot biomass when treated with the biofertilizers plus sulfur and *Acidithio bacillus* or triple superphosphate, and the results were significantly different compared to those of other P treatments in a study by Stamford et al. [20]. This study demonstrated the importance of

sulfur and biofertilizer as catalysts to improve the availability of P from superphosphate or adsorption sites on soil particles. Plants' need for P in semi-arid regions is known [21]. This can be associated with enzymatic pathways that improve drought tolerance in dual-yield crops. P-associated enzymes are important because P can enhance the root apical growth in dual-yield crops, extending water absorption [22].

2.3. Potassium (K)

Potassium is associated with transpiration, enzyme regulation, and various physiological reactions within crops. It is thus responsible for physiological, metabolic, and morphological processes in many crops, including dual-yield crops. The most common fertilizer containing potassium is muriate of potash, which contains 60 to 62% K_2O. Although a significant effect on the number of flowers was observed, the application of potash showed no effect on days to 50% flowering on African yam bean in a study by Mgbeze and Ikhajiagbe [23]. This can be associated with the potassium nutrient responsible for reaction processes rather than the developmental processes of the crop. The effect is dependent on the application amounts. For example, application of 550 kg K/ha produced 192.75 $\pm$ 9.87 flowers per plant compared to 145.13 $\pm$ 18.02 flowers per plant with lower K application (110 kg K/ha). Mgbeze and Ikhajiagbe [23] also found that the grain yield per hectare increased significantly with increasing levels of K application. This can be associated with the effect of K on guard cells, which have a direct influence on stomatal regulation under water stress, thereby improving yields [24]. The stomatal regulatory feature of K could be ideal in water deficit productions because yield and seed components may increase. However, increased biological yield is not guaranteed, making improved tuber yield uncertain.

K application is unlikely to cause toxicity. As such, most researchers have applied it pre-sowing using various amounts. Lestari et al. [15] applied 11.25 g/plant K using potash top dressing on sorghum prior to sowing. Akamine et al. [16] applied 50 g/m^2 K using top discing-in prior to the sowing of amaranths. These applications are simple and need no calculations. However, split application of 75 kg/ha K at 7 and 21 days after planting was also successfully used in zucchini using top dressing by Warisman et al. [12]. Notably, the authors used NPK fertilizer, which increased the availability of all N, P, and K when applied. This splitting technique is necessary when applying fertilizers containing more than a single nutrient as it can prevent toxicities from excess N and P. Similarly, natural fertilizers also require split application to avoid complicated scheduling of nutrient release. For example, de Souza et al. [17] applied cattle manure at planting and potash at 21 days after planting to maintain K availability throughout the season. This application is particularly beneficial in semi-arid regions because manure improves soil water holding capacity, while potash ensures consistent K availability.

2.4. Trace Minerals

Trace minerals are typically found in adequate amounts in many soils or growing media. However, their importance in plants is well documented. Zinc, an important trace element in crops, is known to play a crucial role as a metal component of enzymes responsible for structural, functional, and regulatory functions such as cellular concentrations within crop tissues [25]. Manganese, another vital trace mineral, is a key constituent of chloroplasts associated with photosynthesis. It is the activator of many enzymes responsible for functional activities within a crop. Manganese activates decarboxylase and dehydrogenase and is a constituent of complex PSII-protein, SOD and phosphatase [26]. Iron is vital for the functioning of guard cells in stomata, influencing water use efficiency. The concentration of iron relative to that of calcium determines whether a plant closes or opens its guard cells, which enhances the water use efficiency of a plant. The recent literature has indicated guard cell gene expression when plants are subjected to drought and that the guard cell is an important hub for water stress memory [27].

Studies have demonstrated that combined foliar spray application of Zn and Mn during flowering increases pumpkin grain yield under drought conditions. Yousefi [28] found that increasing irrigation volume reduced yield, indicating that Zn and Mn were responsible for the response of the crop to water shortage. These minerals may have activated drought tolerance by the activation of responsive enzymes within the crop. However, the combined foliar application of Fe and Zn during the development stages showed no correlation with yield in sorghum. Instead, Fe and Zn foliar application combined with normal irrigation showed the highest grain yield and harvest index [29]. Further research into trace minerals on various functions and structural changes is necessary for the association of dual yield and drought tolerance.

3. Effects of Fertilizers on Metabolic Constituents in Dual-Yield Crops

The range in which metabolites are synthesized is premised on the mineral nutrient concentration available for plant uptake. When nutrients exceed the required levels, toxicity occurs, altering metabolite synthesis. For example, proximate concentrations in various African yam bean accessions under ideal mineral nutrient conditions vary. Baiyeri et al. [30] reported the following variations in the concentration of nutritional parameters in different accessions of African yam beans: crude protein (21.84–23.41%), crude fat (3.40–3.86%), fiber (6.17–6.76%), carbohydrates (52.8–54.48%), dry matter (90.42–90.6%), and ash (4.22–4.35%), as well as moisture content (9.4–9.58%) when grown under ideal ecological conditions.

Application of phosphorus (P) on yam bean (*Pachyrhizus erosus* L. Urban) increases the total N in shoot dry matter [20]. Ohanmu et al. found that Cd stress increased the total N content in AYB from 2.03% to 2.03% and 1.93% to 5.73% at 6 and 18 weeks, respectively [31]. These interactions between nutrients availability, where one nutrient affects another, necessitate phytochemical characterization using minor elements. Baiyeri et al. [30] assessed concentrations of different micronutrients and found that AYB contained 312–58 mg/100 g (Se), 10.40–6.07 mg/100 g (Fe) and 8.83–6.37 mg/100 g (Zn). Abioye et al. described the effect of drought condition on the phytochemical concentration of some crops [32]. The authors reported that the concentrations of Ca (48–33 mg/100 g), K (10.83–14.56 mg/100 g), Fe (4.77–8.03 mg/100 g) and P (108–135 mg/100 g) varied in seeds of *Sphenostylis Stenocarpa* grown in a water deficit environment.

It is also important to characterize the effect of minerals on crops based on uptake form. Ohanmu et al. [31] found that the concentration of N in leaves and roots of AYB plants sown on soils without N showed that 6.29% was absorbed in the form of nitrate, while 0.16% was absorbed as ammonium nitrate. Phytochemical content varies depending on nutrient molecule availability, which can be highly correlated with soil available water content.

Abioye et al. [32] reported variations in concentrations of vitamin C (4.37–5.67 mg/g), Beta-carotene (56.67–93.33 μg/g), tannin (6.67–23.33 mg/g), hemagglutinin (0.13–0.57 mg/g), oxalate (6.6.7–15 mg/g), trypsin inhibitor (0–0.47 mg/g) and phytate (16.66–33.33 mg/g) from nine accessions of AYB. This characterization based on the concentration of secondary metabolites can be crucial during assessment of the drought effect on the yield (seeds) and yield components of dual-yield crops.

Water plays a regulatory role in plant growth, affecting biochemical concentrations, physical properties and metabolic structures. Bako and Aguda found that AYB seed surface area, flakiness ratio, porosity, sphericity, aspect ratio, static angle of repose, volume, dynamic angle of repose and static coefficient of friction increased with an increase in seed moisture content [33]. Researchers should associate these changes with metabolic changes during fertilization studies of dual-yield crops (Table 1).

Table 1. The effect of different fertilizers on the metabolism of dual-yield crops.

Fertilizer	Crop Common Name	Scientific Name	Response	References
N	Zucchini	*Cucurbita pepo* L.	Increased leaf chlorophyll index	[12]
N	Sweet sorghum	*S. bicolor*	• Increased proline, soluble protein, hydrocyanic acid, superoxide dismutase, peroxidase, catalase, bate peroxidase • Decreased superoxide anion, hydrogen peroxide, malondialdehyde	[13]
NPK	Sweet sorghum	*Sorghum bicolor*	Increased dry matter	[14]
Cow dung	Amaranth	*Amaranthus spinosus*	Increased alkaloid, flavonoid, tannin, saponin, ash, moisture, protein	[19]
P	Yam bean	*Pachyrhizus erosus*	Increased shoot N	[20]
K	African yam bean	*Sphenostylis stenocarpa*	No effect on foliar dry weight	[23]
Cd	African yam bean	*S. stenocarpa*	Increased shoot and root N	[31]
NPK	White Guinea yam	*Dioscorea rotundata*	Increased shoot and tuber dry weight	[34]
Humic substances	Sweet sorghum	*S. bicolor*	Increased total bioethanol yields	[35]
Chicken manure	Sweet sorghum	*S. bicolor*	Increased sap content	[36]
Goat manure	Sweet sorghum	*S. bicolor*	Increased sap content	[36]
Cow manure	Sweet sorghum	*S. bicolor*	Increased sap content	[36]
Vermicompost	Sweet sorghum	*S. bicolor*	Decreased sap content	[36]
K	Sweet sorghum	*S. bicolor*	Increased dry matter, sugar yields, stalk N content	[37]
Poultry manure	Amaranth	*Amaranthus cruentus* L.	Increased fresh and dry weight	[38]
NaCl	Amaranth	*Amaranthus tricolor* L.	Increased chlorophyll content	[39]
NPK	Amaranth	*Amaranthus tricolor* L.	Increased fresh and dry weight	[40]
Stillage	Amaranth	*Amaranthus hybridus* L.	Increased leaf pigments	[41]
ZnO	Pumpkin	*Cucurbita moschata* Duch.	• No effect on chlorophyll and anthocyanin • Increased amino acid content, protein, total sugar, reducing sugars	[42]
Cd	Pumpkin	*Cucurbita pepo* L.	Reduced seedling superoxide dismutase, catalase, peroxidase, Isocitrate lyase, malate synthase	[43]
N	Pumpkin	*Cucurbitapepo L. convar. Pepo var. styriaca* Greb	Increased leaf chlorophyll-a, carotenoids	[44]
Dekap	Pumpkin	*Cucurbita pepo* L.	• No effect on protein, potassium, phosphorus content • Reduced seed oil percent	[45]
P, vermicompost	Pumpkin	*Cucurbita pepo var.* styriaca	• Increased seed oil yield and quality • Reduced seed zinc content	[46]
NPK	Pumpkin	*Cucurbita moschata*	Increased chlorophyll content	[47]
Se, I	Pumpkin	*Cucurbita pepo* L. ssp. *pepo*	Increased leaf anthocyanin levels	[48]
KNO_3, K_2SO_4, KCl	Pumpkin	*Cucurbita pepo* L.	Increased seed nutrient content	[49]
Ash	Pumpkin	*Cucurbitamoschata* Duch. Ex Poiret L.	Reduced growth, chlorophyll, carotenoid, biochemical content, proline	[50]
N + Si	Zucchini	*Cucurbita pepo* L.	Increased chlorophyll a/b ratio	[51]
Cow dung	Zucchini	*Cucurbita pepo* L.	No effect on leaf chlorophyll	[52]
K_2SiO_4	Squash	*Cucurbita pepo*	Increased fruit-relative water content, N, P, and K content, antioxidant enzyme activities	[53]
NK	Zucchini	*Cucurbita pepo* L.	Increased fruit moisture content	[54]

N, nitrogen; P, phosphorus; K, potassium; Se, selenium; NaCl, sodium chloride; ZnO, zinc monoxide; K2SO4, potassium sulphate.

4. Effects of Fertilizers on the Physiology of Dual-Yield Crops

Respiration, Transpiration, and Photosynthesis

Fertilizer application is arguably the second most important activity in the cultivation of crops in water deficit environments. Research has shown that application of NPK, S, or I directly affects the respiration rate of dual-yield crops, such as pumpkin [47,48]. The nutrient responsible for respiration is believed to be Ca and K due to their association

with the opening and closing of guard cells in stoma. The cellular concentrations of the nutrients are significantly influenced by the relative presence of other nutrients in the growth media. However, not all macronutrients affect the availability of Ca or K. The application of N fertilizer was shown to have no effect on the stomatal conductance and transpiration in pumpkin [55]. However, de Azevedo et al. demonstrated that cow dung application increased the stomatal conductance and transpiration in pumpkin plants [52].

Respiration and transpiration rates are central to all activities that influence yield components. Fertilizer effects on either process result in a change in the development rate of plants. Application of NPK was shown to reduce days to flower opening and number of days to harvest in zucchini [56]. Azab et al. discovered that K_2SiO_3 fertilizer increased fruit photosynthetic pigments and antioxidant enzyme activities [53]. The use of K_2SiO_3 can be explored to develop fertilizer schedules that enhance the activities of enzymes responsible for plant response to drought conditions. Transpiration determines the amount of water a plant absorbs from the growth media. Water is a critical input for photosynthesis, which produces assimilates that determine the biological yield. Most growers apply NPK to improve the physiological reactions in dual-yield crops. Nitrogen contributes a direct effect to the production of assimilates as it is a major constituent of chlorophyll. Shehab and Guo [13] demonstrated that the application of N fertilizer increases the photosynthetic rate, stomatal conductance, and transpiration rate, which are physiological reactions associated with water shortages. There are vast physiological responses of dual-yield crops to fertilizers reported in the literature (Table 2). These can inform strategies for acclimatizing these crops to water scarcity.

Table 2. The effect of different fertilizers on the physiology of dual-yield crops.

Fertilizer	Crop Common Name	Scientific Name	Response	Reference
N	Sweet sorghum	*Sorghum bicolor*	• Increased photosynthetic rate, stomatal conductance, transpiration rate • No effect on internal CO_2	[13]
Cd	Pumpkin	*Cucurbita pepo* L.	Reduced germination percentage, seedling vigor	[43]
NPK	Pumpkin	*Cucurbita moschata*	• Increased stomatal conductance	[47]
Poultry dung	Pumpkin	*Cucurbita moschata*	Increased absolute growth rate (AGR), relative growth rate (RGR)	[47]
Se, I	Pumpkin	*Cucurbita pepo* L. ssp. *pepo*	Increased leaf respiration	[48]
N + Si	Zucchini	*Cucurbita pepo* L.	Increased maximum fluorescence, variable fluorescence, quantum yield of photosystem II	[51]
Cow dung	Zucchini	*Cucurbita pepo* L.	• Increased photosynthesis, stomatal conductance, transpiration • No effect on internal CO_2 concentration, leaf temperature	[52]
K_2SiO_4	Squash	*Cucurbita pepo*	• Increased fruit photosynthetic pigments, antioxidant enzyme activities	[53]
N	Pumpkin	*Cucurbita moschata* Duch.	• No significant effect on stomatal conductance, chlorophyll, photosynthesis, transpiration	[55]
NPK	Zucchini	*Cucurbita pepo*	Reduced number of days to opening of flower to harvest, number of days to first harvest, number of days to last harvest	[56]
NPK	Winged bean	*Psophocarpus tetragonolobus*	• Increased plant stands at harvest (K/ha), days of 50% flowering, days to pod setting	[57]

N, nitrogen; P, phosphorus; K, potassium; Se, selenium; K_2SO_4, potassium sulphate.

5. Effects of Fertilizers on the Morphology of Dual-Yield Crops

5.1. Sink–Source Relationship

The management of assimilates' source and sink in single-yield crops is generally straightforward during the development of yield components. Leaves produce assimilates and send them to the economic yield parts where they sink. However, balancing the sink–source relationship in dual-yield crops is complicated by the simultaneous or sequential development of yield products, leading to competition or inadequate assimilate reserves for later-forming yield parts. Jebril et al. [58] discovered that elimination of the grain sink prior to anthesis significantly increased °Brix, wet and dry biomass, and total sugar by 18, 28, and 43%, respectively, on the stover of sweet sorghum. This presents an opportunity for a grower to sacrifice the yield that develops earlier (grain) or optimize nutrient availability to enhance both yield products throughout the growing period, complicating the scheduling of fertilizer application. Both stover and grain yields have been shown to increase after application of NPK fertilizer [14]. However, excessive NPK application beyond the threshold necessary for assimilate loading or partitioning into the later-yielding component (stover) may be toxic to the crop. Supplying nutrients beyond the quantity needed is known to hamper crop growth and development before reaching a toxic level.

Although the sequential existence of yield brings a challenge to the scheduling availability of major nutrients that affect development such as N, some nutrients may have a minimal effect on the photosynthate partitioning amongst yields. For instance, K application had no significant influence on above- and below-ground parameters of the African yam bean [23], with a negligible effect on root yield and most flowering parameters, except for a noticeable change in the number of reproductive branches. The difference in grain parameters was only observed on the 100-seed weight that increased with an increase in the amount of K applied. Although this can be crop-specific, Mgbeze and Ikhajiagbe [23] found a significant correlation between dry weight and other yield parameters. These correlations greatly depend on the availability of all major nutrients during dual-yield development. Ohanmu et al. [31] discovered that the increase in the concentration of cadmium (Cd) resulted in an increase in shoot and root N contents. Cadmium, a toxic heavy metal, adversely affects quality when the produce is consumed. The availability of cadmium at moderate concentrations is normally not a major concern but has an effect on other nutrients' availability for plant uptake, which is influenced by water availability regulating soil cation exchange capacity (CEC) and soil film concentrations.

5.2. Cellular Reactions

The concentration of cellular sap increases during drought or in crops grown under water deficit environmental conditions. This occurs because drought reduces the water available for plant absorption, thereby increasing the concentration of micro-elements, particularly heavy metals like Zn, Cu, Fe and others that are normally overlooked during fertilization. The application of ZnO was found to increase the concentration of amino acid content, protein, total sugar, and reducing sugars of pumpkin [42]. Notably, these findings are not directly related to the availability of macroelements or water in the soil but rather to the availability of zinc for plant uptake.

Plant cells with high concentrations of nutrients due to water shortages will cause an osmotic imbalance with the neighboring cells. This situation is detrimental to crop growth and development, especially in the presence of infectious pathogens. Adequate moisture, however, reduces the spread of a disease within a plant, which enables some branches to reach the yielding stage. Therefore, analyzing secondary nutrients that affect the concentration of cellular solutes is as vital as fertilization in water deficit environments.

Harsono et al. [36] demonstrated the effectiveness of various manures in increasing the cellular sap of sweet sorghum. This can be attributed to the crop's morphological response within the plant. Application of K_2SiO_3 was reported to increase periderm thickness, cortex thickness, midrib thickness, mesophyll thickness, number of xylem vessels per main vascular bundle, vascular bundle, collenchymatous tissue, and epidermis thickness in

squash leaves [53]. These changes resulting from fertilization can condition crops to thrive under water deficit environments. Various fertilizers elicit distinct reactions that can be explored and associated with water use efficiency in dual-yield crops (Table 3).

Table 3. The effects of different fertilizers on the morphology of dual-yield crops.

Fertilizer	Crop Common Name	Scientific Name	Response	Reference
N	Zucchini	*Cucurbita pepo* L.	Increased in plant length, number of leaves, leaf area, fresh weight, dry weight, number of fruits, fruit weight	[12]
N	Sweet sorghum	*S. bicolor*	Increased leaf number, leaf area index, plant height	[13]
NPK	Sweet sorghum	*Sorghum bicolor*	Increased plant height, leaf area index, grain yield, stover yield	[14]
Organic matter	Sweet sorghum	*S. bicolor*	Increased seed weight, stover weight, extended root length	[15]
NPK	Sweet sorghum	*S. bicolor*	Increased seed weight	[15]
P, NP, or PK	Amaranth	*Amaranthus* spp.	Increased stem diameter, stem weight, leaf area index, fresh leaf weight, and dry leaf weight	[16]
K	Amaranth	*Amaranthus* spp.	• Reduced stem weight, and dry leaf weight Increased stem diameter, leaf area index, fresh leaf weight	[16]
PK	Amaranth	*Amaranthus* spp.	• Increased stem diameter Reduced stem weight, fresh shoot weight, dry leaf weight, and leaf area	[16]
K	African yam bean	*Sphenostylis stenocarpa*	No effect on root length, root nodules, root dry weight	[23]
N	Sweet sorghum	*S. bicolor*	Increased lignocellulosic biomass	[35]
Chicken manure	Sweet sorghum	*S. bicolor*	Increased plant height, stem diameter, leaf area index, stover weight, number of seeds	[36]
Goat manure	Sweet sorghum	*S. bicolor*	• Increased plant height, leaf area index, number of seeds • Decreased stem diameter, stover weight, panicle length	[36]
Cow manure	Sweet sorghum	*S. bicolor*	• Increased plant height, leaf area index, number of seeds • Decreased stem diameter, stover weight, panicle length	[36]
Vermicompost	Sweet sorghum	*S. bicolor*	Increased plant height, stem diameter, leaf area index, stover weight, number of seeds	[36]
K	Sweet sorghum	*S. bicolor*	Increased stalk length, stalk diameter, fresh and dry weight, weight ranges of 1000 grains, grain, biomass	[37]
NPK or Poultry manure	Amaranth	*Amaranthus cruentus* L.	Increased plant height, number of leaves, leaf area, shoot length and root length, seed yield per plot	[38]
NaCl	Amaranth	*Amaranthus tricolor* L.	• Reduced plant height • No effect on number of leaves	[39]
NPK	Amaranth	*Amaranthus tricolor* L.	Increased plant height, number of leaves, leaf area, shoot length and root length	[40]
Stillage	Amaranth	*Amaranthus hybridus* L.	Increased plant height, leaf area, stem girth, number of leaves, leaf fresh and dry mass	[41]
N	Pumpkin	*Cucurbitapepo L. convar. Pepo var. styriaca* Greb	Increased seed yield	[44]

Table 3. *Cont.*

Fertilizer	Crop Common Name	Scientific Name	Response	Reference
Dekap	Pumpkin	*Cucurbita pepo* L.	• Increased plant length, number of auxiliary branches, leaf number, fruit diameter, seed number, seed length • Reduced number of female flowers, number of fruits per plant, fruit fresh weight	[45]
P, vermicompost	Pumpkin	*Cucurbita pepo var.* styriaca	Increased seed number	[46]
Poultry dung, cow dung	Pumpkin	*Cucurbita moschata*	Increased length of vine, leaf number, leaf area, leaf dry weight	[47]
Poultry dung	Pumpkin	*Cucurbita moschata*	Increased internode length, initiated flowers, fresh plant biomass, leaf area index (LAI), leaf area ratio (LAR), leaf area duration (LAD)	[47]
NPK	Pumpkin	*Cucurbita moschata*	Increased petiole length	[47]
Se, I	Pumpkin	*Cucurbita pepo* L. ssp. *pepo*	No effect on fruit and seed yield	[48]
KNO_3, K_2SO_4, KCl	Pumpkin	*Cucurbita pepo* L.	Increased seed grain yield	[49]
Ash	Pumpkin	*Cucurbitamoschata* Duch. Ex Poiret L.	Reduced fruit yield	[50]
Ash	Pumpkin	*Cucurbitamoschata* Duch. Ex Poiret L.	Increased number of flowers and fruits, fruits' length and diameter, fresh and dry weight of fruits	[50]
K_2SiO_3	Squash	*Cucurbita pepo*	Increased periderm thickness, cortex thickness, midrib thickness, mesophyll thickness, number of xylem vessels per main vascular bundle, vascular bundle, collenchymatous tissue and epidermis thickness	[53]
K_2SiO_3	Squash	*Cucurbita pepo*	Increased plant height, fresh and dry weight of root and shoot, fruit yield	[53]
NK	Zucchini	*Cucurbita pepo* L.	Increased fruit size	[54]
NPK	Zucchini	*Cucurbita pepo*	Increased diameter of fruit, length of fruit, weight of fruit, number of fruits per plant and fruit yield per plant	[56]
NPK	Winged bean	*Psophocarpus tetragonolobus*	Increased pods per plant, pod length, number of seeds per pod, 100-seed weight	[57]
Poultry manure or NPK	Amaranth	*Amaranthus cruentus* L.	Increased number of branches and stem diameter	[59]
NPK or cow dung	Pumpkin	*Telfairia occidentalis*	Reduced average number of leaves, branches, internode length	[60]
NPK	Pumpkin	*Telfairia occidentalis*	Increased stem girth	[60]
Cow dung	Pumpkin	*Telfairia occidentalis*	Reduced stem girth	[60]
NPK	Pumpkin	*Cucurbita moschata* POIR.	Increased seed yield	[61]

N, nitrogen; P, phosphorus; K, potassium; Se, selenium; NaCl, sodium chloride; K_2SO_4, potassium sulphate.

6. Associating Fertilizers with Physiology, Metabolism, Morphology, and Yields in Water Deficit Environments

The association between physiology and drought tolerance in dual-yield crops entails altering the concentration of enzymes responsible for pathways, resulting in lower consumption of water by the crops. The development of drought tolerance in dual-yield crops is complicated by the fact that vegetative parts cannot be altered to accommodate a single yield. For example, application of high-N fertilizer increases the sorghum stalk and grain yield but reduces the sugar yield. The application of biofertilizer was reported to enhance physiological tolerance to drought stress by improving the antioxidant enzymes

in medicinal pumpkin (*Cucurbita pepo* convar. pepo var. Styriaca) [62]. This increase in antioxidant compounds benefits the medicinal aspect of the yield but degrades taste and flavor on vines and fruits meant for consumption if a concentration of bitter compounds increases. The activity of catalase, ascorbate peroxidase (APX), glutathione reductase (GR), guaiacol peroxidase (GPX) and nitroxin enzymes was improved using mycorrhiza as a catalyst of nutrient availability [62]. These enzymes are known to improve drought tolerance and can be manipulated through fertilization.

Application of ammonium was found to cause flower abortion in Italian zucchini, resulting in no fruit formation during harvesting [63]. The ammonium reduced competition for photosynthates between vegetative and reproductive parts. The findings can be utilized to condition the development of dual-yield crops to avoid fruit development if a drought period is approaching during a growing season. The authors also reported that the type of fertilizer determines the physiological changes the zucchini displayed. The general growth, gas exchange, and photochemical efficiency were higher in nitrate-fertilized plants compared with ammonium-fertilized plants [63]. This suggests that if crops with water shortages are fertilized with nitrate N, their physiological reactions will be better than those under the application of ammonium N.

Application of fertilizer to improve dual-yield crop metabolism and morphology in drought conditions can be affected by the availability of the water holding capacity of the fertilizer. Organic fertilizer, such as manure, has a higher water holding capacity than synthetic fertilizers like urea. Application of water-reserving organic sources of nutrients, such as compost, is ideal in temporary drought conditions and in improving dual-yield crops. Turp et al. [64] found that biomass yield (stover height and weight), juice yield, and sugar concentration increase when ash and vermicompost are applied instead of synthetic fertilizers under hot and dry conditions. Lestari et al. [15] demonstrated that NPK improves only the seed yield in sweet sorghum, while different organic matter composts improved both the stover and the seed yield, as well as the root length. Increased root length allows plants to access soil moisture from deeper horizons, an ideal survival technique under drought conditions.

Harsono et al. [36] investigated the effects of different livestock manures in sweet sorghum growing in dry conditions and found that chicken manure performs better than cow, goat, or vermicompost manures. Chicken manure increases biological yield (plant height, stem diameter, leaf area index, stover weight, number of seeds, and sap content) in two sorghum varieties. The increase in the biomass and high sap content of the sorghum varieties is associated with an increase in the sugar and carbohydrate contents, the assimilates that assist plants during growth and development.

Potassium fertilizer application increases grain yield, stover N content, biomass, sugar, and water use efficiency in sorghum [37]. The availability of potassium was proven to improve the N metabolism in the stover, enhancing the production of assimilates and increasing stover and leaf size. This beneficial change affects photosynthesis and respiration, as K concentration improves the functioning of guard cells in the stomata of plants under water stress conditions [24].

7. Research Gaps and Recommendations

The future of research on fertilizer application to improve dual-yield crops' response to drought conditions lies in the exploration of neglected crops and uninvestigated parameters. Numerous dual-yield crops, such as zucchini, winged bean, tuber cowpea, and tuber vetchling, have been largely overlooked in fertilization-based research focused on drought tolerance. These species lack comprehensive research on most aspects related to fertilization and irrigation. Research examining fertilizer response to improve physiology, metabolism, and morphology within the same species, and their association to drought tolerance, is limited. It is well established that adaptation to changing environments varies with the level of genetic diversity within a crop species. Analysis of population indices and genetic diversity amongst subspecies and varieties is pivotal for decoding plant adaptation to

dynamic environmental stressors like drought [65]. The use of polymerase chain reaction (PCR)-based molecular markers can be explored to comprehend accurate genetic differences within a crop population to supplement the known features of crops that possess a favorable fertilizer reaction that enhances drought tolerance. Research exploring the application of trace minerals to dual-yield crops under water deficit environments is very scarce. Future studies can also associate the effects of different fertilizers with the vegetative or reproductive morphology and physio-metabolic changes required for improving water use efficiency.

8. Summary

Nitrogen fertilizer application has been shown to improve physiological processes that alter metabolism to manifest a morphology that can be associated with response to drought tolerance. Various phytochemicals linked to the water use efficiency of plants were found to respond to N applications. Studies exploring the secondary effects of single fertilizers indicated complex relationships between nutrients. For instance, sulfur and biofertilizers were demonstrated as catalysts that improve the availability of P from superphosphate. These nutrients' interactions also impact yield quantity and quality. The form in which a nutrient fertilizer is absorbed by a plant influences assimilate partitioning into sink organs of dual-yield crops. The application of nitrate N and ammonia N were found to differently affect leaf and root phytochemical contents, which were highly affected by water availability for plant uptake. Leaf and root characterization based on the metabolism of dual-yield crops is the most potent form of coding for drought tolerance. However, there are various other methods that can be utilized to improve accuracy. The use of polymerase chain reaction (PCR)-based molecular markers and other gene coding methods remains underexplored for comprehending genetic differences in fertilizer responses that improve drought tolerance within crop populations.

9. Conclusions

The current literature on the fertilization of dual-yield crops primarily focuses on macronutrients. However, research exploring the effects of trace minerals on the metabolism, physiology, and morphology of dual-yield crops is very limited. This lack of information hinders efforts in making evidence-based recommendations for the technical production of dual-yield crops, since there is no established research foundation to inform the relationships between various nutrients. Further research in this field is strongly recommended.

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