**Yield and Growth of Different Amaranth Genotypes under varying water regimes.**

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**Abstract**

**Traditional vegetables are piloted as champion species for sub-Saharan Africa, a region experiencing high nutritional food insecurity and water scarcity. Amaranth is one of the traditional vegetables that has excellent potential to be commercialized in South Africa. The study's main objective was to assess the effect of different water regimes on six amaranth genotypes that were used to generate a MAGIC population as well as two reference genotypes. An experiment was conducted under rain shelters at ARC-VIMP, Roodeplaat Pretoria, Gauteng, during the 2020/2021 and 2021/2022 summer seasons. The experiment was laid out in a 3 x 4 factorial treatment in a completely randomized design with amaranth genotypes (VI060472, VI061494, VI044371, VI062433, VI061487, VI050446, Arusha and Anna,) and water levels {20-25% (W1), 60-65% (W2), and 80-85% (W3)}, replicated three times, of each genotype/water level combination. Data collected included total fresh and dry biomass, total fresh and dry leaf mass (t ha-1), leaf number, fresh and dry leaf mass in grams per plant and initial and final plant height. The study's findings showed that there was a highly significant difference as well as an interaction effect for water levels and genotypes for the selected variables. Total dry biomass ranged from 32.93 to 61.36 t ha-1, and dry leaf mass per plant from 6.43 g to 18.35 g. Higher productivity was observed from the VI061494 genotype. Therefore, this genotype can be recommended to farmers who want to commercialize Amaranth; they will attain higher productivity, assuming that agronomic management is the same.**

***Keywords*:** biomass, crop productivity, leafy vegetables, population

**INTRODUCTION**

Amaranth is one of the underutilized crops in South Africa but very promising in alleviating hunger and a nutritious food crop for human consumption (Förster et al., 2023; Emmanuel and Babalola, 2022). The genus includes several grain and leafy species widely distributed in South and Southern Africa, occurring as a weed in crop fields and widely eaten in communities as a spinach-like vegetable (Gerrano et al., 2015). Many regions of the world cultivate and eat amaranth species as leafy vegetables. The leaves of young grain varieties can be used as a herb sauce, and there is no obvious distinction between vegetable and grain species. Four species *Amaranthus cruentus*, *A*. *dubius*, *A. blitum,* and *A. tricolor* have been known to be widely grown as vegetables. However, depending on the producer's target market, *A. cruentus* can be grown as a grain as well as a vegetable. Vegetable amaranth is a widely harvested crop and one of the most popular important leafy vegetables in South Africa. Amaranth is an annual, fast-growing plant and is easily cultivated in gardens and fields. Similar to spinach, amaranth leaves have been utilized as greens. They have a wonderful, slightly sweet flavor and may be used fresh as a salad or cooked (Aderibidge et al., 2022).

In South Africa, there are reports of amaranth use in several areas of Limpopo, KwaZulu-Natal, North-West, and Mpumalanga provinces (Managa and Nemadodzi 2023). In many Sub-Saharan African (SSA) nations, African Indigenous Vegetables (AIV) constitute a staple of the local population diet (Bokelmann et al., 2022). Indigenous vegetable crops are well suited for resource poor households because they occupy smaller areas (kitchen gardens), take a shorter period of time to mature (thus readily available), require low external agricultural production practices (grow naturally in the ‘‘wild’’ or on the fallow, without fertilization and irrigation, which make them cheaper and easily accessible), easy to harvest on daily basis and without a need for storage (Nyathi et al., 2016). Amaranth has excellent nutritional value due to their high content of macro- and micronutrients like β-carotene, iron, calcium, vitamin C and folic acid, calcium, iron, magnesium, phosphorus, potassium, zinc, copper, and manganese compared with *Vigna unguiculata* (L.) Walp. It is a very good source of vitamins including vitamin A, vitamin K, vitamin B6, vitamin C, riboflavin, folate (Achigan-Dako et al., 2014; Maseko, 2014; Abolaji et al*.,* 2017; Kumar et al., 2020; Nyonje et al., 2021; Ruth et al., 2021; Aderibidge et al., 2022).

Drought and salt stress are among the main abiotic stresses recognized globally. The primary abiotic factor that limits plant growth and development is drought, which also lowers agricultural crop yield (Oluk et al., 2023; Yadav et al., 2022. It is a moderate loss of water which results in stomatal closure and limitation in gas exchange. In order to live, the crop reacts to drought stress in a variety of physiological and biochemical ways and is highly harmful to pigments (Wang et al., 2022). The physiological characteristics of plants, such as chlorophyll concentration, photosynthetic parameters, biomass, and yield, are impacted by drought (Zhao et al., 2020). Because it is the most severe and common abiotic stress that reduces the potential production of crops, drought is one of the major problems facing agriculture globally. Most crops are vulnerable to drought and can lose more than 50% of their yield (Rida et al., 2021). Under drought stress, plants restrict their stomata to lessen water loss through transpiration (Hlatshwayo, 2018).

In South Africa, amaranth production is mostly at the research level and is harvested from the wild (Emmanuel and Babalola 2021). It grows well in summer and is one of the common indigenous vegetables. It is grown massively in homeland provinces like KwaZulu-Natal, Mpumalanga, Northwest and Limpopo. The most predominant species are *A. thunbergii*, *A. greazican*, *A.* *spinosus*, *A. deflexus*, *A.hypochondriacus*, *A.viridis* and *A.hybridus* (Olusanya et al., 2021). The major constraint limiting the production of African leafy vegetables is poor seed quality as farmers rely on retained seeds of landraces. Continued use of landraces and lack of improved cultivars means that productivity remains low (Shayanowako et al., 2021). Drought is caused by decreased precipitation and increased temperature, and it is the most important limiting factor for crop productivity and, ultimately, food security worldwide (Zhang et al., 2018).

**MATERIALS AND METHODS**

**Planting material**

Six multiple-parent advanced generation inter-cross (MAGIC) parental amaranth genotypes were obtained from Asian Vegetable Research and Development Centre (AVRDC), also known as The World Vegetable Centre in Taiwan and two from the Agricultural Research Council- Vegetables, Industrial and Medicinal Plants gene bank (Table 1).

**Experimental site**

The experiments were conducted under two rain shelters at the Agricultural Research Council – Vegetable, Industrial and Medicinal Plants, Roodeplaat, Pretoria (South Africa), (25060”S; 28035’’E; 1168 masl) Gauteng Province. The meteorological data were obtained from Agricultural Research Council- Soil, Climate and Water (ARC-SCW) automatic weather station network. Weather data maximum and minimum air temperature, maximum and minimum relative humidity, precipitation, wind speed and reference evapotranspiration [ET0] during the experiment period were monitored by the automatic weather station (AWS) situated within 100m radius from the rain shelters (Table 2). The rain shelters have rain sensors that trigger an electric motor during a rainfall event and the shelter automatically covers the experimental trial. Therefore, the experiment experienced normal field conditions except when it is raining (Nyathi et al., 2016.

Table 1. Evaluated MAGIC anAmaranth genotypes and their origin

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **No** | **Germplasm** | **Genotype** | **Species** | **Origin** |
| 1 | AVRDC | VI060472 | *hypochondriacus* | Tanzania |
| 2 | AVRDC | VI061494-A | *cruentus* | Madagascar |
| 3 | AVRDC | VI044371 | *cruentus* | Ghana |
| 4 | AVRDC | VI062433 | *hypochondriacus* | Uknown |
| 5 | AVRDC | VI061487 | *cruentus* | United State of America |
| 6 | AVRDC | VI050446 | *hypochondriacus* | Sudan |
| 7 | ARC | Arusha | *cruentus* | Tanzania |
| 8 | ARC | Anna | *hypochondriacus* | Germany |

AVRDC- Asian Vegetable Research and Development Centre, ARC- Agricultural Research Council

Table 2. Monthly mean weather data and daily evapotranspiration, at automatic weather station in Roodeplaat

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Month** | **Temperature (ᵒC)** | | **Relative Humidity (%)** | | **Wind Speed**  **(m s-1)** | **Daily ET0 (mm)** |
| **2020/2021** | **Max** | **Min** | **Max** | **Min** |
| January | 35.7 | 16.9 | 93.8 | 30.8 | 1.0 | 4.3 |
| February | 36.0 | 15.4 | 95.9 | 31.6 | 0.9 | 4.0 |
| March | 37.0 | 10.8 | 97.4 | 24.6 | 0.8 | 4.2 |
| April | 28.4 | 10.4 | 96.2 | 21.5 | 0.7 | 3.6 |
| May | 27.9 | 3.8 | 95.9 | 19.7 | 0.7 | 2.9 |
| **2021/2022** |  |  |  |  |  |  |
| January | 29.2 | 15.8 | 95.9 | 38.5 | 0.7 | 4.3 |
| February | 31.3 | 14.9 | 95.6 | 30.4 | 0.9 | 4.8 |
| March | 28.9 | 14.2 | 95.7 | 34.2 | 0.7 | 3.7 |
| April | 24.5 | 10.1 | 97.6 | 38.8 | 0.8 | 2.8 |
| May | 24.3 | 5.4 | 97.9 | 27.4 | 0.7 | 2.7 |

Legend: Max: Maximum, Min: Minimum, ETo: daily reference evapotranspiration

Prior to commencement of the trial in each cropping season, soil samples from 30 cm topsoil were collected and analysed in analytical laboratory at the Institute of Vegetables, Industrial and Medicinal Plants of the Agricultural Research Council. This was done in order to determine chemical and physical properties of the soil at the study site (Table 3). The soil at the study site is classified as a Hutton soil form (Soil Classification Working Group, 1991) with a loamy texture.

**Experimental layout and treatments**

The two-factor field experiment included eight Amaranth genotypes and three irrigation levels in two rain shelters (one rain shelter with four Amaranth genotypes and three water levels). It was set up according to the randomized complete block design (RCBD) with three replications. The individual plot size was 4.6 m2 (2.4 m x 1.9 m) with a net plot area of 1.8 m2, six plant rows per plot, 9 plants in a row and a total of 54 plants in each plot and 1 m spacing between the blocks with inter-row and intra-row spacing of 0.3 m x 0.3 m making a total of 111111 plants ha-1.

The distance between the blocks was 1 m. The irrigation treatments were as follows:

* Irrigation treatment (W1): Soil refilled to field capacity (FC) when 20-25% of available soil water (ASW) was depleted.
* Irrigation treatment (W2): Refilled to FC when 60-65% of ASW was depleted.
* Irrigation treatment (W3): Refilled to FC when 80-85% of ASW was depleted.

Table 3: Physical and chemical properties of soil from the experimental site (average values)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Properties** | **Rain shelter 7** |  | **Rain shelter 8** |  |
| **2020/21 summer season** | **2021/22 summer season** | **2020/21 summer season** | **2021/22 summer season** |
| pH (H2O) | 8.19 | 8.13 | 7.64 | 7.22 |
| P (Bray2)(mg kg-1) | 75 | 40 | 172 | 217 |
| K (mg kg-1) | 128 | 125 | 88 | 68 |
| Ca (mg kg-1) | 1480 | 1260 | 795 | 703 |
| Mg (mg kg-1) | 563 | 428 | 260 | 260 |
| Na (mg kg-1) | 105 | 110 | 30 | 93 |
| Exchangeable cation Ca (%) | 57.6 | 59.2 | 61.3 | 56.3 |
| Exchangeable cation Mg (%) | 36 .2 | 33.3 | 33.2 | 34.4 |
| Exchangeable cation K (%) | 2.6 | 3 | 3.5 | 2.8 |
| Exchangeable cation Na (%) | 3.6 | 4.5 | 2 | 6.5 |
| Clay (%) | 41 | 35 | 17 | 18 |
| Silt (%) | 7 | 5 | 4 | 2 |
| Sand (%) | 52 | 60 | 79 | 80 |
| N-NO3 | 0.8 | 5.65 | 0.2 | 21.8 |
| N-NH4 | 0.85 | 0.6 | 0.8 | 0.7 |

**Soil water content**

Soil water content was measured using neutron probe water meter, model 503DR CPN Hydroprobe (Campbell Pacific nuclear Inc, California, USA) that measures volumetric water content for irrigation scheduling, pre-calibrated on the experimental site. Access tubes were installed in the middle of each plot and the reading were taken at 0.2 m intervals to a depth of 1.0 m by lowering the probe through the access tubes once a week to determine the water depletion level before irrigation.

**Irrigation**

Drip irrigation system was used to apply water under the rain shelter. The system consisted of pump, filters, solenoid valves, water meters, control box, online drippers, 2000 litre JOJO tank, main line, sub-lines, and laterals. The system was designed to allow for maximum operating pressure of 200 kPa with average emitters discharge of 2 l.h-1. Drip lines were spaced according to the plant spacing (0.3 m x 0.3 m). Irrigation scheduling was based on the measured depletion of available soil water (ASW). To help the plants establish, all treatments received the same amount of water for the first two weeks; after that, irrigation treatments were implemented. To guarantee water availability throughout the day's peak demand periods, irrigation was carried out three times a week, in the morning. After accounting for the initial watering, the total amount of applied water in 2020/2021 for rain shelter 7 was in range from 461 mm (20-25%-well watered) to 321 mm (60-65%-moderate stressed) and 174 mm (80-85%- severe stressed) and for rain shelter 8 from 464 mm to 319 mm and 186 mm, respectively. During the 2021/2022 season, the total water applied for rain shelter 7 was in range from 348 mm (20-25%-well watered) to 285 mm (60-65%-moderate stressed) and 157 mm (80-85%- severe stressed) and for rain shelter 8 from 400 mm to 278 mm and 171 mm, respectively.

**Agronomic practices**

Seeds were sown in polystyrene trays with 200 cells filled with commercial growing medium, Hygromix® (Hygrotech Seed Pty. Ltd, South Africa) on the 11-12 January 2021 for first season and 10-11 January 2022 for the second season. The substrate in the trays was covered with vermiculite to minimize water loss from the surface. Emergence started three to six days after sowing. Seedlings were transplanted four weeks after sowing. During the first two weeks after planting (WAP) all irrigation treatments received an equal amount of water which ranged from 1.2 mm day-1 to 6.5 mm day-1 depending on the weather. This was done to ensure an adequate crop establishment before deficit irrigation commenced. During 2020/21 season, only limestone ammonium nitrate (LAN 28%) fertilizer was applied at the recommended rate of 150 kg ha-1from 4 weeks after transplanting and 8 weeks after transplanting and no fertilizer applied during 2021/22 based on the soil analysis results .

**Data collection**

In all rows, planting was done by hand at 1 cm depth opened by hand. A total of five (5) plants per plot, which were not harvested, were randomly tagged for data collection. Initial plant height was measured at fourteen weeks after transplanting from the tagged plants using a measuring tape before the commencement of the water treatments and the final plant height during the last harvest. Harvesting commenced six weeks after transplanting (WAT) and every two weeks thereafter and only plants between rows were used for data collection to avoid the border effect. During harvesting, the above ground portion of the amaranth plant was cut at 0.2 m above the soil surface. At each harvest, the fresh biomass of the above ground part of the plant was determined from the surface of 1.8 m2 (27 plants) of each treatment and the total fresh biomass (t ha-1) was calculated after completion of all harvests. Five additional plants were also harvested to determine the number of leaves per plant, as well as leaf fresh and dry mass in grams per plant in each treatment.

At each harvest, the leaves were separated from the stem to determine the fresh weight of the leaves of each treatment and the average of leaf fresh mass (g) was achieved during multiple harvests to determine the marketable yield of amaranth. The harvested material was then separated into stems and leaves. For accuracy of results, plant sample weights were measured within an hour of collection to minimise moisture loss. Dry matter content was obtained after oven drying at 70°C for 48 hours. Crop growth rate (CGR) explains the dry matter production per unit of land area per unit time and is calculated using the following formula (Ramesh et al., 2019):

CGR = (g m-2 day-1) (1)

W1 and W2 = plant dry weight per unit area at t1 andt2, respectively; t1 = first sampling, t2 = second sampling.

**Data analysis**

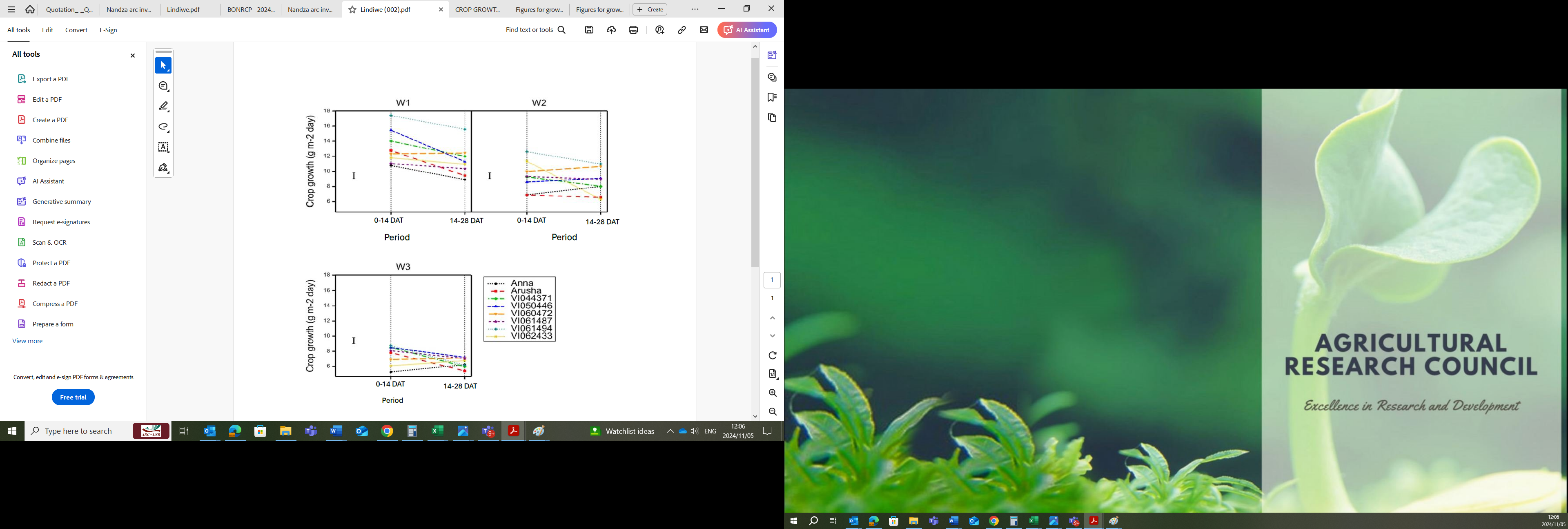
The data were subjected to analysis of variance using SAS software (version 9.4) at a 5% probability level.  Tukey honest significant difference (p<0.05) was used to separate significant means.

**RESULTS AND DISCUSSION**

**Growth parameters**

*1. Crop growth rate*

Figure 1 shows the average CGR for both seasons of rain shelter trial for all genotypes. The CGR was calculated for the period from 0 to 14 and 14 to 28 days after transplant (DAT). As expected, all genotypes had the highest CGR under the W1 irrigation regime during the period from 0 to 14 DAT, and the lowest at W3 during the period from 14 to 28 DAT. Genotype ‘VI061494’ had the highest CGR under all irrigation regimes during both growth periods (from 0 to 14 and from 14 to 28 DAT), except in W3 during the period 14 to 28 DAT. Under the W1 irrigation regime, all cultivars had a lower CGR in the period 14 to 28 DAT than in the first growth period from 0 to 14 DAT, except for the genotype ‘VI060472’ which had a higher CGR in the later period. This pattern was also seen for this genotype under irrigation regimes W2 and W3. Genotype ‘VI062433’ showed the least reduction in CGR between irrigation regimes W1 and W2 during the first growing period (0 to 14 DAT), but CGR did dramatically drop during the second growth period in W2 compared to W1. Numerous research investigations have demonstrated that CGR, assessed at various growth stages, can serve as a proxy for net canopy photosynthesis (Ramesh et al., 2019).

Figure 1. Crop growth rate of amaranth genotypes under different water levels (average of 2020/21 and 2021/22), W1-well-watered, W2-moderate stressed, W3-severe stressed

*2. Number of leaves for two growing seasons and varying water regimes*

Within a genotype, the number of leaves did not differ between growing seasons (Table 4). All genotypes except ‘VI061494’ had a range of 77 (‘Anna’ in season 2) to 109 (‘VI050446’ in season 1). VI061494 had a lower number of leaves, 55 in season 1 and 2 respectively (Table 4). The leaf number increased with an increase in water application (Table 5). The level of irrigation had a significant effect on the number of leaves of all genotypes, except for ‘VI06149494’, which had a statistically equal number of leaves in all irrigation regimes (71, 53 and 44). All other genotypes had the highest number of leaves under the W1 irrigation regime. However, all genotypes with the exception of ‘VI060472’, had a statistically equal number of leaves under W2 and W3 irrigation, that is, the severe stressed condition compared to moderate, did not result in a significantly lower number of leaves. The highest productivity (yield) was observed for the ‘VI061494’ genotype due to the fact that it had broad leaves, thick stem, and wide variation for this genotype, despite this genotype having the lowest number of leaves.

Table 4: Effect of growing season on amaranth genotype yield and growth parameters

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Genotypes** | **Year** | **TFBio**  **(t ha-1)** | **TDBio**  **(t ha-1)** | **TLFM**  **(t ha-1)** | **TLDM**  **(t ha-1)** | **LN** | **LFM**  **(g plant-1)** | **LDM**  **(g plant-1)** | **IPH (cm)** | **FPL**  **(cm)** |
| VI060472 | S1 | 70.84a | 42.59a | 39.14ab | 22.89a | 112a | 32.71abc | 7.18ab | 21.01 | 99.88de |
|  | S2 | 61.69defg | 30.43def | 30.33de | 17.97bcd | 99a | 28.15bc | 6.31b | 17.86 | 94.68e |
| VI061494 | S1 | 71.65a | 42.78a | 42.13a | 22.61a | 59bc | 41.43ab | 9.57ab | 20.96 | 150.54a |
|  | S2 | 68.46ab | 42.16a | 32.69cd | 23.04a | 54c | 41.78ab | 9.52ab | 20.52 | 143.48a |
| VI044371 | S1 | 60.09efg | 33.77bcd | 35.97bc | 18.38b | 102a | 36.19abc | 8.67ab | 17.59 | 130.70abc |
|  | S2 | 59.03efgh | 31.72de | 24.31f | 14.96e | 88abc | 35.61abc | 8.24ab | 17.34 | 120.89bcde |
| VI062433 | S1 | 65.93bcd | 32.87cd | 30.39de | 18.46b | 90abc | 35.24abc | 11.44ab | 19.4 | 104.24cde |
|  | S2 | 59.39efgh | 28.89efg | 28.81def | 18.25bc | 81abc | 31.43abc | 12.60a | 21.04 | 94.37e |
| VI061487 | S1 | 66.22bc | 37.32b | 35.83bc | 22.73a | 106a | 38.17abc | 9.68ab | 19.17 | 124.22abcd |
|  | S2 | 57.28gh | 27.94fgh | 27.97ef | 17.95bcd | 98ab | 36.35abc | 8.99ab | 18.7 | 115.41cde |
| VI050446 | S1 | 62.90cde | 35.43bc | 30.33de | 20.03b | 109a | 43.34a | 10.15ab | 21.72 | 113.94cde |
|  | S2 | 61.91cdef | 32.94cd | 30.42de | 17.66bcd | 99a | 43.23a | 9.15ab | 20.29 | 109.12cde |
| Arusha | S1 | 57.99fgh | 26.23gh | 26.50ef | 18.02bcd | 92abc | 26.35c | 6.83ab | 18.7 | 116.14cde |
|  | S2 | 55.45h | 26.80fgh | 26.31ef | 15.77de | 84abc | 26.88bc | 7.44ab | 16.37 | 119.78bcde |
| Anna | S1 | 58.20fgh | 27.77fgh | 25.20f | 15.98cde | 93ab | 26.26c | 7.35ab | 16.67 | 108.56cde |
|  | S2 | 55.48h | 24.91h | 28.65def | 17.66bcd | 77abc | 27.84bc | 7.43ab | 15 | 112.09cde |

Means values followed by the same letter within the column are not significantly different by Tukey’s HSD.

Legend: S1 – growing season 2020/2021, S2 – growing season 2021/2022, TFBio-Total Fresh Biomass, TDBio-Total Dry Biomass, TLFM- Total Leaf Fresh Mass, TLDM- Total Leaf Dry Mass, LN -Leaf Number, LFM - Leaf Fresh mass, LDM - Leaf Dry Mass, IPH - Initial Plant Heigh, FPH - Final Plant Height

*3. Initial and final plant height for two growing seasons and varying water regimes*

There was no significant difference observed within the genotypes in the initial plant height during the first and second season (Table 4). With regards to the final plant height, the highest was observed in ‘VI061494’ for first and second seasons with an average of 150.54 cm and 143.48 cm, respectively. The lowest final plant height was observed for ‘VI062433’ with an average of 94.37 cm. Water regimes showed no significant effect on initial plant height. (Table 5). Even though there was no statistically significant differences for final plant height, the trend was an increase in plant height with an increase in water application as for leaf number (Table 5). Final plant height was consistently higher in well-watered (W1) compared to moderate (W2) and severe stressed (W3). The highest final plant height (152.30 cm) for the well-watered W1 regime was observed in ‘VI061494’ while the lowest was (105.67 cm) in ’VI060472’. These results concur with those of Maseko (2018), indicating that limiting water application could lead to reduced leaf number and plant height.

**Yield parameters**

*1. Total fresh and dry biomass for two growing seasons and varying water regimes*

In the first season (S1) total fresh biomass ranged from 57.99 to 71.65 t ha-1 (‘Arusha’ and ‘VI061494’, respectively), while in the second season (S2) it was slightly lower from 55.45 to 68.46 t ha-1, (‘Arusha’ and ‘VI061494’, respectively)(Table 4). Similarly, the total dry biomass ranged from 26.23 to 42.78 t ha-1 (‘Arusha’ and ‘VI061494’, respectively) during the S1 and from 24.91 to 42.16 t ha-1 (‘Anna’ and ‘VI061494’, respectively) during the S2. The difference in results between the two seasons could be attributed to differences in weather conditions (humidity and temperature). Specific combinations of genotype and season, ‘VI061494’ x S1, ‘VI060472’ x S1 and ‘VI061494’ x S2, achieved statistically equal highest total fresh biomass (71.65, 70.84 and 68.46 t ha-1, respectively) and total dry biomass (42.78, 42.59 and 42.16 t ha-1, respectively). This indicates the stability of the genotype ‘VI061494’ for these traits, regardless of seasonal temperature variation. On the contrary, the genotypes ‘VI0640472’, ‘VI062433’ and ‘VI061487’ which achieved lower values ​​of total fresh and dry biomass in the second season, showed greater sensitivity to less favourable temperature conditions (Table 2). The two ARC genotypes ‘Arusha’ and ‘Anna’, achieved the lowest total fresh and dry biomass in both research seasons.

The interaction of the researched genotypes and well-watered irrigation level (W1) resulted in the highest total fresh biomass in the widest range from 66.44 t ha-1 (‘Arusha’) to 86.61 t ha-1 (‘VI061494’), as well as total dry biomass from 32.93 t ha-1 (‘Anna’) to 61.36 t ha-1 (‘VI061494’) (Table 5). The interaction of the genotypes with the moderate stress irrigation level (W2) resulted in lower total fresh and dry biomass in a narrower range, while with the severe stress irrigation level (W3) it had the lowest values of the mentioned parameters in the narrowest range. In the interaction with W2, the range of total fresh biomass was from 56.03 t ha-1 (‘Arusha’) to 69.60 t ha-1 (‘VI061494’) and of total dry biomass from 24.01 t ha-1 (‘Anna’) to 40.01 t ha-1 (‘VI061494’). These values were achieved by interaction with the same genotypes as in above mentioned interaction with W1. In the interaction with W3, the range of total fresh and dry biomass was from 47.18 t ha-1 ('VI050446') to 53.96 t ha-1 ('VI061494') and from 21.17 t ha-1 ('Arusha') to 26.74 t ha-1 ('VI061487'), respectively. The interactions of genotypes ‘VI061494’ and ‘VI060472’ with the W1 level of irrigation had the significantly highest total fresh biomass (86.61 and 82.2 t ha-1, respectively) while the interaction of ‘VI061494’ and W1 also achieved the highest total dry biomass (61.36 t ha-1), significantly higher than the other researched interactions. The lowest total fresh biomass without statistical difference was achieved by W3 in interaction with all genotypes, except ‘VI061494’. Also, the lowest total dry biomass without statistical difference was achieved by the interaction of W3 with all genotypes and by interaction of W2 with genotypes ‘Arusha’ and ‘Anna’. The findings are in line with that of Beletse et al. (2012) and Nyathi et al. (2016) that A. *cruentus* grown in the less irrigated treatment produced the least average biomass yield on fresh and dry weight basis. The present study showed that genotypes differ in their yield in response to seasonal variation and water deficit.

Table 5. Effect of irrigation level on amaranth genotype yield and growth parameters

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Genotypes** | **Water regime** | **TFBio**  **(t ha-1)** | **TDBio**  **(t ha-1)** | **TLFM**  **(t ha-1)** | **TLDM**  **(t ha-1)** | **LN** | **LFM**  **(g plant-1)** | **LDM**  **(g plant-1)** | **IPH**  **(cm)** | **FPH**  **(cm)** | **Water Applied (mm)** |
| VI060472 | W1 | 82.2ab | 45.46b | 44.44ab | 24.63bc | 170a | 35.44abcdefg | 6.43cd | 19.22 | 105.67bcdef | 464 |
|  | W2 | 67.88efg | 37.90de | 34.48def | 21.05def | 100bcde | 33.79bcdef | 8.88bcd | 18.77 | 96.62def | 319 |
|  | W3 | 48.68kl | 26.17hi | 25.28hijklmn | 15.62ijk | 47f | 22.09efg | 4.93cd | 20.32 | 89.55ef | 186 |
| VI061494 | W1 | 86.61a | 61.36a | 49.11a | 30.60a | 71ef | 54.92a | 9.46bcd | 20.87 | 152.3.0a | 461 |
|  | W2 | 69.60def | 40.60cd | 35.34cdef | 20.96def | 53ef | 38.35abcdef | 9.38bcd | 22.73 | 149.6a | 321 |
|  | W3 | 53.96jk | 25.45hij | 27.78ghijkl | 16.91hij | 45f | 31.55bcdefg | 9.79bc | 18.62 | 139.62ab | 174 |
| VI044371 | W1 | 73.36cde | 41.15bcd | 40.63bc | 21.15def | 138ab | 44.25abc | 12.03abc | 18.48 | 130.55abcd | 461 |
|  | W2 | 57.98hij | 33.10fg | 28.18ghik | 16.12hij | 80efd | 28.32cdefg | 7.21cd | 17.67 | 125.65abcd | 321 |
|  | W3 | 47.35l | 23.99ij | 21.62mn | 12.75k | 67ef | 35.13bcdefg | 6.11cd | 16.25 | 120.18abcde | 174 |
| VI062433 | W1 | 76.62bc | 41.01bcd | 37.57cde | 22.87cde | 153a | 41.88abcd | 18.35a | 22.08 | 112.72bcde | 461 |
|  | W2 | 63.77fgh | 28.86gh | 29.40fghi | 16.87hij | 64ef | 34.89bcdefg | 9.37bcd | 20.97 | 96.10def | 321 |
|  | W3 | 47.59l | 22.79ij | 21.84lmn | 15.32jk | 40f | 23.24defg | 8.32bcd | 17.62 | 89.10ef | 174 |
| VI061487 | W1 | 75.27cd | 39.09d | 48.01a | 26.52b | 149a | 49.18ab | 16.26ab | 17.30 | 136.20abc | 461 |
|  | W2 | 60.26hi | 32.05fg | 27.23ghijklm | 20.19efg | 83cdef | 29.14cdefg | 6.12cd | 22.08 | 120.18abcde | 321 |
|  | W3 | 49.73kl | 26.74hi | 20.47n | 14.30jk | 74ef | 33.45bcdefg | 5.64cd | 17.38 | 103.07cdef | 174 |
| VI050446 | W1 | 77.68bc | 44.71bc | 38.32cd | 23.83bcd | 155a | 45.12abc | 12.12abc | 22.33 | 120.52abcde | 464 |
|  | W2 | 62.36gh | 32.09fg | 29.32fghi | 17.38ghij | 76ef | 43.40abc | 11.12abc | 21.05 | 110.57bcde | 319 |
|  | W3 | 47.18l | 25.76hij | 23.49jklmn | 15.33jk | 81cdef | 41.39abcde | 5.70cd | 19.63 | 103.52cdef | 186 |
| Arusha | W1 | 66.44fg | 33.68ef | 32.01efg | 19.21fgh | 127abc | 33.97bcdefg | 10.46abc | 17.05 | 137.13abc | 464 |
|  | W2 | 56.03ij | 24.70hij | 24.35ijklmn | 16.75hij | 69ef | 25.79cdefg | 5.17cd | 17.05 | 133.78abc | 319 |
|  | W3 | 47.69l | 21.17j | 22.85klmn | 14.69jk | 68ef | 18.10g | 5.87cd | 18.50 | 82.37f | 186 |
| Anna | W1 | 66.68fg | 32.93fg | 30.52fgh | 18.73fghi | 126abcd | 31.33bcdefg | 12.85abc | 18.01 | 112.98bcdef | 464 |
|  | W2 | 56.33ij | 24.01ij | 27.00ghijkl | 16.44hij | 72ef | 31.71bcdefg | 7.56cd | 16.07 | 110.77bcdef | 319 |
|  | W3 | 47.50l | 22.07ij | 23.26jklmn | 15.29jk | 58ef | 20.10gf | 1.76d | 14.50 | 106.77bcdef | 186 |
| *HSD* |  | 1.32 | 1.07 | 1.37 | 0.71 | 11 | 4.42 | 1.80 | 2.06 | 7.94 | 10.2 |

Means values followed by the same letter within the column are not significantly different by the Tukey’s HSD.

Legend: W1 – well-watered irrigation level, W2 – moderate stress irrigation level, W3 – severe stress irrigation level, TFBio-Total Fresh Biomass, TDBio-Total Dry Biomass, TLFM- Total Leaf Fresh Mass, TLDM- Total Leaf Dry Mass, LN - Leaf Number, LFM - Leaf Fresh mass, LDM - Leaf Dry Mass, IPH -Initial Plant Height, FPH - Final Plant Height

*2. Total leaf fresh and dry mass for two growing seasons and varying water regimes*

For the total leaf fresh mass, ‘VI061494’ had highest yield of 42.13 t ha-1 during the first season while in second season, ‘VI061494’ was the highest with 32.69 t ha-1 (Table 4). During the first season, ‘Arusha’ had the least total fresh mass of 26.31 t ha-1 whereas ‘VI044371’ had the least total fresh mass of 24.31 t ha-1 for the second season. Total leaf dry mass ranged from 15.98 t ha-1 (‘Anna’) to 22.89 t ha-1 (‘VI060472’) during the first season and in the second season it ranged from 14.96 t ha-1 (‘VI44371’) to 23.04 t ha-1 (‘VI061494’).

When genotypes were subjected to different water regimes, it was notable that under well-watered irrigation level (W1), ‘VI061494’ was the highest with 49.11 t ha-1 and the lowest total leaf fresh mass had interaction of well-watered irrigation level (W1) and genotype Anna (30.52 t ha-1) (Table 5). A trend was observed when increasing water stress, the total leaf mass decreased. Both seasons' results show that a significant amount of water is required for successful amaranth production. It was worth noting that the yield was reduced when increasing water stress for both seasons.

*3. Leaf fresh and dry mass in grams per plant*

In the first season, leaf fresh mass ranged 26.26 to 43.34 g plant-1 (‘Anna’ and ‘VI50446’, respectively) and during the second season, it ranged from 26.88 to 43.23 g plant-1 (‘Arusha’ and ‘VI050446’, respectively) (Table 4). Furthermore, the interactions of the genotype and season ‘VI050446’ x S1, ‘VI061494’ x S1, ‘VI050446’ x S2 and ‘VI061494’ x S2 achieved statistically highest leaf fresh mass (43.34, 41.43, 43.23 and 41.78 g plant-1, respectively). Leaf dry mass ranged from 6.83 to 11.44 g plant-1 (Arusha and VI062433, respectively) during the first season and in the second season, it ranged from 6.31 to 12.60 g plant-1 (‘VI60472’ and ‘VI062433’, respectively). Varying water regimes significantly affected the yield of amaranth genotypes. The interaction of genotypes with the well-watered irrigation level (W1) resulted in higher leaf fresh mass in the widest range from 31.33 g plant-1 (‘Anna’) to 54.92 g plant-1 (‘VI050446’). However, it was recognized that the leaf fresh mass of VI050446 was not affected by water stress.

**CONCLUSIONS**

The key findings from the results showed that amaranth genotypes vary in agronomically relevant production and yield traits. Water availability had a significant effect on the growth and leaf yield of amaranth genotypes, with well-watered plants showing higher growth and yield than those under severe water stress conditions. During the first season (S1), all the traits evaluated were higher than in the second season (S2). This might be due to the higher temperatures in season 1 that led to the increase in application of water. It was noticeable that genotype ‘VI061494’ was the highest in most of the traits evaluated in all water levels except number of leaves. Therefore, this genotype can be recommended to farmers who want to commercialize amaranth; they will attain higher productivity, assuming that agronomic management is the same.

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**Literature cited**

Abolaji, G.T., Olooto, F.M., Ogundele, D.T., and Williams, F.E. (2017). Nutritional characterization of grain amaranth grown in Nigeria for food security and healthy living. Agrosearch. *17*(2), 1-10 http://dx.doi.org/10.4314/agrosh.v17i2.1.

Achigan-Dako, E.G., Sogbohossou, O.E.D., and Maundu, P. (2014). Current knowledge of Amaranthus species. Research avenues for improved nutritional value and yield in leafy Amaranthus in sub-Saharan Africa. Euphytica. *197*, 303-317.

Aderibidge, O.R., Ezekiel, O.O., Owolade, S.O., Korese, J.K, Sturm, B., and Hensel, O. (2022). Exploring the potentials of underutilized grain amaranth (Amaranthus spp.) along the value chain for food and nutrition security: A review. Critical Reviews in Food Science and Nutrition *62*(2), 656-669.

Beletse, Y., du Plooy, I., and Jansen van Rensburg, W. (2012). Chapter 5, Water requirement of selected african leafy vegetables. nutritional value and water use of African Leafy Vegetables for Improved Livelihoods. WRC Report No. TT 535/12, 100.

Bokelmann, W., Huyskens-Keil, S., Ferenczi, Z., and Stober, S. (2022). The role of indigenous vegetables to improve food nutrition security: Experiences from the project HORTINLEA in Kenya (2014-2018). Frotiers in Sustanable Food Systems *6*, 806420 https://doi.org/10.3389/fsufs.2022.806420.

Emmanuel, O.C., and Babalola, O.O. (2022). Amaranth production and consumption in South Africa: The challenges of sustainability for food and nutrition security. International Journal of Agricultural Sustainability *20*(4), 449-460.

Förster, N., Dilling, S., Ulrichs, C., and Huyskens-Keil, S. (2023). Nutritional diversity in leaves of various amaranth (Amaranthus spp.) genotypes and its resilience to drought stress. Journal of Applied Botany and Food Quality *96*, 1-10 https://doi.org/10.5073/JABFQ.2023.096.001.

Gerrano, A.S., Jansen van Rensburg, W.S., and Adebola, P.O. (2015). Genetic diversity of Amaranthus species in South Africa. South African Journal of Plant and Soil *32*(10), 39-46.

Hlatshwayo, N. (2018). Position of Amaranthus seed on the plant in relation to seed quality and productivity under varying water regimes (MSc Dissertation, UKZN, South Africa).

Kumar, D., Kumar, S., and Shekhar, C. (2020). Nutritional components in green leafy vegetables: A review. Journal of Pharmacognosy and Phytochemistry *9*(5), 2498-2502.

Ladejobi, O., Elderfield, J., Gardner, K.A., Gaynor, R.C., Hickey, J., Hibberd, J.M., Mackay, I.J., and Bentley, A.R. (2016). Maximizing the potential of multi-parent crop populations. Applied and Translational Genomics *11*, 9-17.

Managa, G.M., and Nemadodzi, L.E. (2023). Comparison of agronomic parameters and nutritional composition on red and green Amaranth species grown in open field versus greenhouse environment. Agriculture *13*(3), 685 https://doi.org/10.3390/agriculture13030685.

Maseko, I. (2018). Pre-and post-harvest response of selected indigenous leafy vegetables to water stress (Doctoral dissertation, Ph. D. Thesis. University of KwaZulu–Natal, South Africa).

Mncwango, N.C., Van Jaarsveld, C.M., Ntuli, N.R. and Mavengahama, S. (2021). Participatory selection of Amaranthus genotypes in the KwaMbonambi Area, KwaZulu-Natal, South Africa. Sustainability. 13(21), 11962 https://doi.org/10.3390/su132111962.

Nyathi, M.K., Annandale, J.G., Beletse, Y.G., du Plooy, C.P., Pretorius, B., and van Halsema,G.E. (2016). Nutritional water productivity of traditional vegetable crops. PhD Thesis. University of Pretoria. South Africa.

Nyonje, W.A., Schafleitner, R., Abukutsa-Onyango, M., Yang, R-Y., Makokha, A., and Owino, W. (2021). Precision phenotyping and association between morphological traits and nutritional content of vegetable amaranth (Amaranthus spp.). Journal of Agriculture and Food Research 5, 10065 https://doi.org/10.1016/j.jafr.2021.100165.

Oluk, C.A., Gönen, E., and Çolak, Y.B. (2023). Effect of different irrigation regimes on the nutritional quality of surface and subsurface drip-irrigated Amaranth under Mediterranean climatic conditions. Gesunde Pflanzen *75*, 1625–1638 https://doi.org/10.1007/s10343-023-00863-y.

Ramesh, S., Sudhakar, P., Elankavi, S., Suseendran, K. and Jawahar, S. (2019). Crop growth rate (CGR), root length, panicle length and grain yield of rice (*Oryza sativa* L.) as influenced by gibberellic acid. Journal of Pharmacognosy and Phytochemistry *8*(2) 1325-1328.

Rida, S., Maafi, O., López-Malvar, A., Revilla, P., Riache, M., and Djemel, A. (2021). Genetics of germination and seedling traits under drought stress in a MAGIC population of maize. Plants, *10*(9), 1786 https://doi.org/10.3390/plants10091786.

Ruth, O.N., Unathi, K., Nomali, N., and Chinsamy, M. (2021). Underutilization Versus Nutritional- Nutraceutical Potential of the Amaranthus Food Plant: A Mini-Review. Applied Sciences *11*(15), 6879 https://doi.org/10.3390/app11156879.

Scott, M.F., Ladejobi, O., Amer, S., Bentley, A.R., Biernaski, J., Boden, S.A., Clark, M., Dell'Acqua, M., Dixon, L.E., Filippi, C.V., et al. (2020). Multi-parent populations in crops: a toolbox integrating genomics and genetic mapping with breeding. Heredity *125*, 396- 416.

Soil Classification Working Group. (1991). Soil Classification: A Taxonomic System for South Africa. Mem. Natural Agric. Resources for S.A. No. 15, 262, Editon 2 (Department of Agricultural Development), 257 p.

Wang, J., Zhang, X., Han, Z., Feng, H., Wang, Y., Kang, J., Han, X., Wang, L., Wang, C., and Li, H. (2022). Analysis of physiological indicators associated with drought tolerance in wheat under drought and re-watering conditions. Antioxidants. *11*, 2266 https://doi.org/10.3390/antiox11112266.

Yadav, P., Mina, U., Bhatia, A., and Singh, B. (2022). Cultivar assortment index (CAI): a tool to evaluate the ozone tolerance of Indian Amaranth (*Amaranthus hypochondriacus* L.) cultivars. Environmental Science and Pollution Research *30*, 30819-30833.

Yan, W., Zhao, H., Yu, K., Wang, T., Khattak, A.N., and Tian, E. (2020). Development of a multiparent advanced generation intercross (MAGIC) population for genetic exploitation of complex traits in *Brassica juncea*: Glucosinolate content as an example. Plant Breeding *139*(4), 779-789.

Zhao, W., Liu, L., Shen, Q., Yang, J., Han, X., Tian, F., and Wu, J. (2020). Effects of water stress on photosynthesis, yield, and water use efficiency in winter wheat. Water *12*(8), 212 https://doi.org/10.3390/w12082127.

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