agronomy

MDPI

Article

Impact of Mid-Season Drought on Tuber Yield, Biomass, Harvest Index, and Water-Use Efficiency of Jerusalem Artichoke in Tropical Regions

Ruttanachira Ruttanaprasert [1,*], Sanun Jogloy [2], Thanawat Kaewkhieo-Ngam [1], Anon Janket [3], Ratchanee Puttha [4] and Chorkaew Aninbon [5]

[1] Department of Plant Science, Textile and Design, Faculty of Agriculture and Technology, Rajamangala University of Technology Isan, Surin Campus, Surin 32000, Thailand; tanawat0883773256@gmail.com
[2] Department of Plant Science and Agricultural Resources, Faculty of Agriculture, Khon Kaen University, Muang, Khon Kaen 40002, Thailand; sjogloy@gmail.com
[3] Department of Agronomy, Faculty of Agriculture, Ubon Ratchathani University, Ubon Ratchathani 34190, Thailand; anon.j@ubu.ac.th
[4] Division of Agronomy, Faculty of Agricultural Production, Maejo University, San Sai, Chiang Mai 50290, Thailand; ratchanee_pt@mju.ac.th
[5] Faculty of Agricultural Technology, King Mongkut's Institute of Technology Ladkrabang, Bangkok 10520, Thailand; chorkaew.an@kmitl.ac.th
* Correspondence: ruttanachira@gmail.com or ruttanajira.ru@rmuti.ac.th

Abstract: Mid-season drought is increasingly recognized as a major constraint on tuber production in Jerusalem artichoke. The ability of different genotypes to maintain high yields under such conditions is a critical component of drought tolerance. This study aimed to investigate the effects of mid-season drought on tuber yield, biomass, harvest index, tuber water-use efficiency (WUEt), and biomass water-use efficiency (WUEb) across various Jerusalem artichoke genotypes with differing levels of drought tolerance. The experiment was conducted in pots using a 2×5 factorial combination in a randomized complete block design with four replications over two years. Factor A consisted of two water regimes: field capacity (FC) and mid-season drought. Factor B included five genotypes: JA 3, JA 125, JA 15, JA 89, and CN 52867. Mid-season drought significantly reduced tuber dry weight, biomass, WUEt, and WUEb, while increasing the harvest index. Significant differences were observed among genotypes for tuber dry weight, biomass, harvest index, WUEt, and WUEb under both water regimes. CN 52867 and JA 89 were characterized as drought-tolerant genotypes with high water-use efficiency and high yield potential. JA 3 was also noted for its lower yield reduction under stress. These three genotypes serve as valuable genetic resources for breeding programs aimed at developing progeny populations with enhanced yield potential and drought tolerance, particularly for mid-season drought-prone environments.

Keywords: drought tolerance; genotype; environment interaction; tuber crop; water deficit; yield reduction

Academic Editor: Alfredo Emilio Rubio Casal

Received: 23 December 2024
Revised: 30 January 2025
Accepted: 30 January 2025
Published: 31 January 2025

Citation: Ruttanaprasert, R.; Jogloy, S.; Kaewkhieo-Ngam, T.; Janket, A.; Puttha, R.; Aninbon, C. Impact of Mid-Season Drought on Tuber Yield, Biomass, Harvest Index, and Water-Use Efficiency of Jerusalem Artichoke in Tropical Regions. *Agronomy* **2025**, *15*, 395. https://doi.org/10.3390/agronomy15020395

1. Introduction

The Jerusalem artichoke (*Helianthus tuberosus* L.), a functional food native to North America, is an underutilized crop with immense potential for promoting human health. It is a rich source of diverse phytochemicals, including inulin [1,2], flavonoids [3], and phenolic acids [4], which can be transformed into high-value products such as pharmaceuticals [2]. Furthermore, its exceptional inulin content positions it as a promising raw material for bioethanol production [5]. This versatile crop thrives in both temperate and tropical climates, making it a viable option for global cultivation.

Drought is a major global challenge that severely impacts agricultural productivity, ecosystems, and plant health. As climate change continues to increase the frequency and intensity of droughts, mitigating their effects has become an urgent priority worldwide. Over 80% of cultivation zones in Thailand, as well as most agricultural regions in the tropics, rely on rain-fed conditions, making them vulnerable to drought at any stage of crop growth. In temperate regions, drought during the early vegetative stage has a relatively smaller impact on final tuber production compared to that in other stages. However, drought during the mid-season or the tuber-initiation stage significantly reduces the tuber yield of the "Nohodka" Jerusalem artichoke variety [6]. Prolonged drought stress has been shown to decrease tuber yield in Jerusalem artichoke by 20% [6,7]. Interestingly, it simultaneously improves water-use efficiency by 7–35% and increases the harvest index by 21% [6]. In tropical regions, combined long-term drought and heat stress can lead to a 29% reduction in tuber yield and a 53% loss in biomass. Despite these challenges, some Jerusalem artichoke genotypes demonstrate resilience and maintain yields to some extent under drought conditions [8]. Mild water stress results in reductions of 7.1% and 9.6% in water-use efficiency for biomass and tubers, respectively. In contrast, severe drought stress causes slight increases in water-use efficiency for biomass (4.2%) and tubers (5.4%) [9]. Terminal-drought stress, however, leads to a substantial reduction in tuber yield, ranging from 40.4% to 63.0% [10]. Several studies have explored the genetic diversity within Jerusalem artichoke, identifying genotypes with varying levels of drought tolerance. Ruttanaprasert et al. [8] found that genotypes such as CN 52867, HEL 53, and HEL 231 consistently exhibited high yields over two consecutive years, demonstrating their potential for drought tolerance. While drought stress adversely affected tuber yield and water-use efficiency, some genotypes, like JA 5, showed a remarkable ability to maintain high yield and water-use efficiency across different water regimes, indicating their suitability for cultivation in drought-prone areas [11]. Ruttanaprasert et al. [12] highlighted that genotypes such as JA 5, JA 60, and JA 125 exhibited high drought tolerance indices for specific root traits, suggesting that superior root development contributes to improved drought resistance and higher tuber yields. Additionally, Janket et al. [9] identified genotypes like HEL 231, HEL 65, and JA102 x JA89(8) as having superior water-use efficiency, making them strong candidates for breeding programs aimed at improving water-use efficiency in drought-prone regions. In response to terminal drought during the growth stages, Chaimala et al. [13] reported that drought-tolerant genotypes such as JA125 and JA4 maintained higher net photosynthetic rates (Pns) and moderate transpiration efficiency (TE), even under drought stress.

The effects of mid-season drought in tropical regions on tuber yield, biomass, harvest index, and water-use efficiency in Jerusalem artichoke have not been thoroughly investigated. This study aimed to evaluate the impact of mid-season drought on these parameters in various Jerusalem artichoke genotypes with differing levels of drought tolerance. This study addresses the following key questions: (1) How does mid-season drought influence tuber yield, biomass, harvest index, and water-use efficiency in Jerusalem artichoke? (2) Are there significant differences in the drought responses of genotypes with varying levels of drought tolerance? (3) Can specific genotypes be identified as more suitable for drought-prone tropical environments based on their physiological and yield responses? The hypotheses of this study assert that mid-season drought considerably diminishes tuber yield, biomass, harvest index, and water-use efficiency in Jerusalem artichoke. Furthermore, drought-tolerant genotypes demonstrate a lesser reduction in these parameters compared to drought-sensitive genotypes. Some genotypes exhibit enhanced performance in drought conditions, rendering them appropriate for cultivation in tropical areas with limited water resources. The results of this research could provide valuable insights for breeders seeking to develop drought-tolerant genotypes. In addition, the findings offer practical knowledge for optimizing water management strategies to enhance the yield of Jerusalem artichoke in agricultural systems.

2. Materials and Methods

2.1. Experimental Design and Treatments

A pot experiment was conducted using a 2 × 5 full factorial treatment in a randomized complete block design with four replications, spanning two years. The first year of this study took place from September 1 to 31 December 2021, and the second year was from 16 December 2022 to 15 March 2023. The experiment was carried out under a rainout shelter at the Field Practice Station of the Department of Plant Science, Textile, and Design, Faculty of Agriculture and Technology, Rajamangala University of Technology, Surin Campus, Thailand (14° 51′N, 103° 29′ E, 146 m above mean sea level).

The experiment included two factors. Factor A represented two water regimes: field capacity (FC) and mid-season drought (maintaining 50% available soil water (50% AW) during 31–60 days after transplanting (DAT)). Factor B consisted of five genotypes of Jerusalem artichoke: JA 3, JA 125, JA 15, JA 89, and CN52867. These genotypes were selected based on their varying levels of drought resistance, as reported by Ruttanaprasert et al. [8]. JA 3 and JA 125 were identified as having low potential yield under severe drought stress but exhibited a high degree of drought tolerance. JA 15 and JA 89 were categorized as having intermediate yield under drought stress with mild drought tolerance. CN52867 displayed high yield potential under drought stress but with a low degree of drought tolerance [8].

2.2. Pot and Plant Preparation

A total of 200 plastic pots, each measuring 35 cm in diameter and 25 cm in height, were prepared by filling each pot with 20 kg of dry soil. The soil was layered evenly into two equal parts to achieve a uniform bulk density of 1.45 g/cm^3 in each pot [11]. Each experimental unit consisted of five pots, with one plant grown per pot.

The tubers were cut into smaller segments, each containing 2–3 buds, and treated by immersion in a carboxamide solution (10 g dissolved in 20 L of water) for 40 min. Following treatment, the tuber pieces were pre-sprouted in a 1:1 mixture of burnt rice husk and Trichoderma under ambient conditions for 4 to 7 days.

After the initial sprouting, the tubers were transferred to germination plug trays filled with a medium consisting of burnt rice husk, Trichoderma, and soil in a 3:2:2 ratio. They were maintained in the trays for an additional 7 days to ensure complete sprouting. The resulting seedlings, characterized by uniformity and the development of 3–4 healthy leaves, were then prepared for transplanting. Carboxamide and Trichoderma were employed to effectively manage stem rot disease caused by *Sclerotium rolfsii*.

2.3. Water Management

Before transplanting, all the pots were irrigated to achieve field capacity (20.73%), and the soil moisture was maintained at this level until 30 DAT to ensure consistent plant establishment. In the well-watered treatment, soil water levels were consistently maintained at field capacity from transplanting until harvest. For the mid-season drought treatment, the soil moisture content was kept at field capacity during 0–30 DAT, reduced to 50% of available water (14.65%) during 31–60 DAT, and then restored to field capacity until harvest. Throughout all treatments, the soil moisture content was uniformly managed with a variance of no more than 1%.

Irrigation was applied to the pots based on the crop's water requirements to sustain the designated soil moisture levels. The water supplied to each pot was equivalent to the sum of water consumed by the crop and the evaporation from the soil surface. The water irrigation volumes were calculated using the methodologies described by Doorenbos and Pruitt [14] and Singh and Russell [15]. The crop water requirement was determined using the following formula outlined by Doorenbos and Pruitt [14]:

$$ETcrop = kc \times ETo \quad (1)$$

where ETcrop represents the crop water need (mm/day); ETo is the reference crop evapotranspiration (mm/day); and kc is the crop coefficient, which varies across growth stages.

Since the crop coefficient (k) for Jerusalem artichoke is not available in the literature, the k value for sunflower was used as a substitute [8,16].

Surface evaporation (Es) was calculated using the methodology described by Singh and Russell [15]:

$$Es = \beta\ (E_0/t) \quad (2)$$

where Es represents soil evaporation (mm); β denotes the light transmission coefficient depending on crop cover; E_0 indicates evaporation from a Class A pan (mm/day); and t represents the number of days since the last irrigation.

During the irrigation treatments, the soil moisture content was measured using the gravimetric method at 7-day intervals to ensure accurate and consistent monitoring.

2.4. Data Collection

2.4.1. Weather and Soil Data

Weather data, including daily measurements of humidity, evaporation (E_0), and maximum and minimum temperatures, were collected from a Surin weather station (14° 53′ N, 103° 30′ E, 145 m above mean sea level) situated 5 km from the experimental field (Figure 1). These observations spanned the period from transplanting to harvest across both years of this study. The soil moisture content was determined gravimetrically at 30, 60, and 90 days after transplanting (DAT). The experimental site featured sandy loam soil, whose chemical and physical properties were thoroughly analyzed.

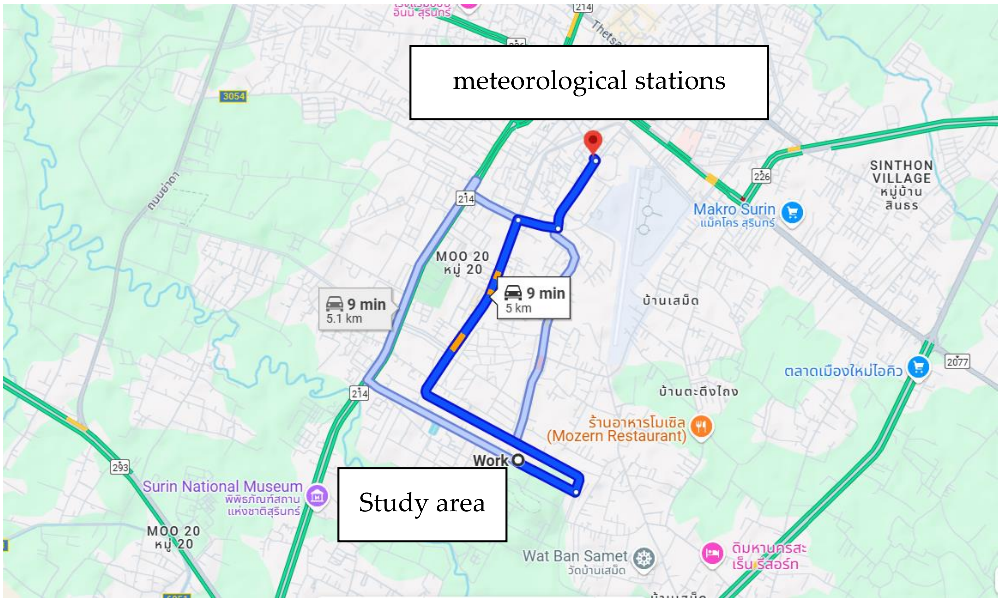

Figure 1. Study area and meteorological stations [17].

2.4.2. Relative Water Content (RWC)

The relative water content (RWC) of each plot was measured at 30, 60, and 90 DAT. Measurements were taken between 10:00 a.m. and 12:00 p.m. using the third fully expanded leaf from the top of the main stem. The assessment followed the methodology outlined by Kramer [18] and Ruttanaprasert et al. [11].

2.4.3. Water-Use Efficiency (WUE)

The total water use was determined by summing the irrigation applications per pot and adjusting for changes in soil moisture from transplanting to harvest. The water-use efficiency (WUE) for tuber and biomass production was calculated based on the formula provided by Teare et al. [19] as follows:

$$\text{WUEt} = \frac{\text{Tuber dry weight}}{\text{Water used in evapotranspiration}} \tag{3}$$

$$\text{WUEb} = \frac{\text{Total biomass}}{\text{Water used in evapotranspiration}} \tag{4}$$

2.4.4. Tuber Dry Weight, Biomass, and Harvest Index

At harvest maturity, two plants per experimental unit were selected and harvested. Each plant was carefully separated into leaves, stems, tubers, and roots. The tubers and roots were thoroughly washed to remove any adhering soil. Mature plants were identified based on 50% defoliation and noticeable stem browning. The harvested samples were then oven-dried at 80 °C until a constant weight was achieved. The dry weights of the leaves, stems, tubers, and roots were recorded separately. The total biomass was calculated as the sum of these individual dry weights. The harvest index was determined by dividing the tuber dry weight by the total biomass.

2.4.5. Reduction Percentage

The sensitivity of Jerusalem artichoke genotypes to mid-season drought stress was evaluated by determining the percentage reduction in tuber dry weight and total biomass for each genotype. This assessment was conducted using the following calculation [11]:

$$\text{Reduction percentage} = \left\{1 - \left(\frac{\text{Weight under drought}}{\text{Weight under non} - \text{drought}}\right)\right\} \times 100 \tag{5}$$

2.5. Statistical Analysis

Analysis of variance (ANOVA) was conducted for each trait using a factorial treatment design within a randomized complete block design (RCBD) [20]. Significant differences ($p \leq 0.05$) among the main effects were determined using the least significant difference (LSD) test. All the statistical analyses were performed using the STATISTIX 10 software [21].

3. Results

3.1. Weather and Soil Data

The average air temperatures during the first and second years ranged from 21.9 to 31.1 °C and 21.2 to 31.7 °C, respectively (Figure 2a,c). The daily pan evaporation rates varied between 0.2 and 5.9 mm in the first year (Figure 2b) and between 0.8 and 7.2 mm in the second year (Figure 2d). The relative humidity was recorded at 77.0% in the first year and 68.7% in the second year (Figure 2b,d).

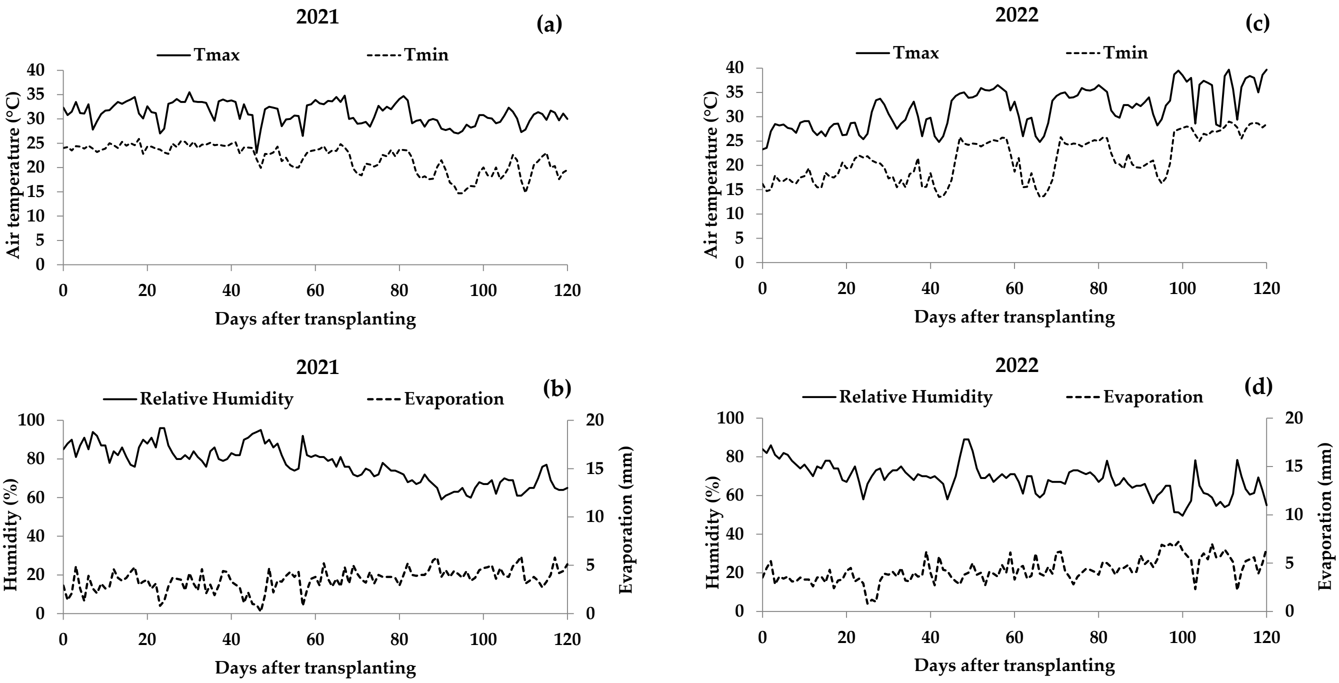

Figure 2. Maximum temperature (Tmax), minimum air temperature (Tmin) (°C), evaporation (mm), and relative humidity (%) during the experiment in 2021 (**a**,**b**) and 2022 (**c**,**d**).

The soil was classified as sandy loam, consisting of 58% sand, 34% silt, and 8% clay. It contained 0.70% organic matter, 0.05% total nitrogen, 7.25 mg/kg phosphorus, and 22.27 mg/kg potassium (Table 1).

Table 1. Soil texture and chemical properties in a pot experiment from June 2021 to June 2024.

Soil Texture	
Sand (%)	58
Silt (%)	34
Clay (%)	8
Soil type	Sandy loam
Soil Chemical Properties	
pH	5.40
EC (mS/cm)	0.11
Organic matter (%)	0.70
Total N (mg/kg)	0.05
P (mg/kg)	7.25
K (mg/kg)	22.27
Ca (mg/kg)	319.96
Mg (mg/kg)	23.05
CEC (cmol/kg)	4.21

3.2. Soil Moisture and Plant Water Status

The differences in soil moisture content between the two water regimes—field capacity (FC; well watered) and mid-season drought (50% available water, AW)—were evident at 60 DAT (Figure 3). The results indicated that the mid-season drought levels were managed effectively. The soil moisture content corresponded to the plant's water status, as reflected by clear differences in RWC between the two water regimes during 31–60 DAT.

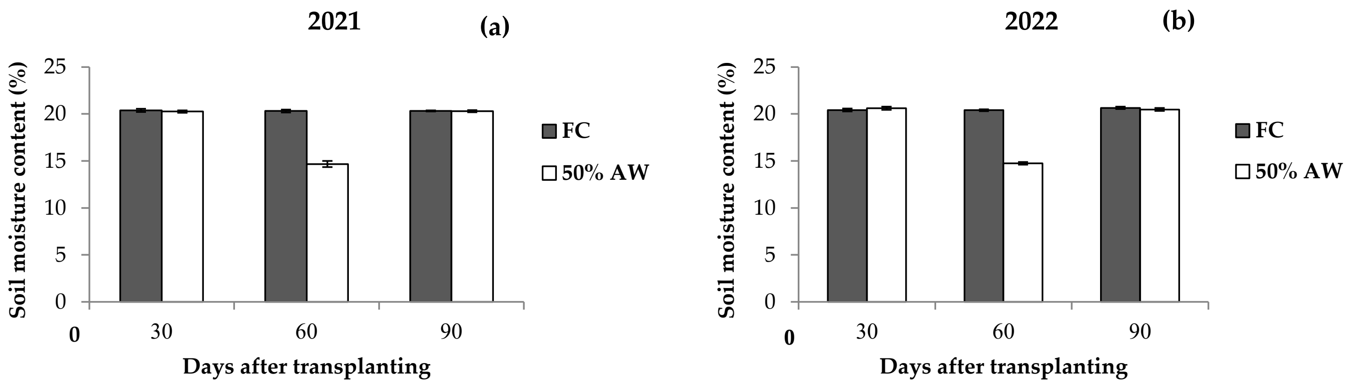

Figure 3. Percentages of soil moisture content at 30, 60, and 90 days after transplanting in 2021 (**a**) and 2022 (**b**).

At 60 DAT, the average soil moisture content was 20.2–20.5% under FC and 14.5–14.8% under 50% AW in 2021 and 20.2–20.6% under FC and 14.5–15.0% under 50% AW in 2022 (Figure 3). Correspondingly, the RWC values ranged from 70.6 to 87.6 in 2021 and from 72.3 to 87.0 in 2022 (Figure 4). The RWC values under FC were significantly higher than those under 50% AW at 60 DAT.

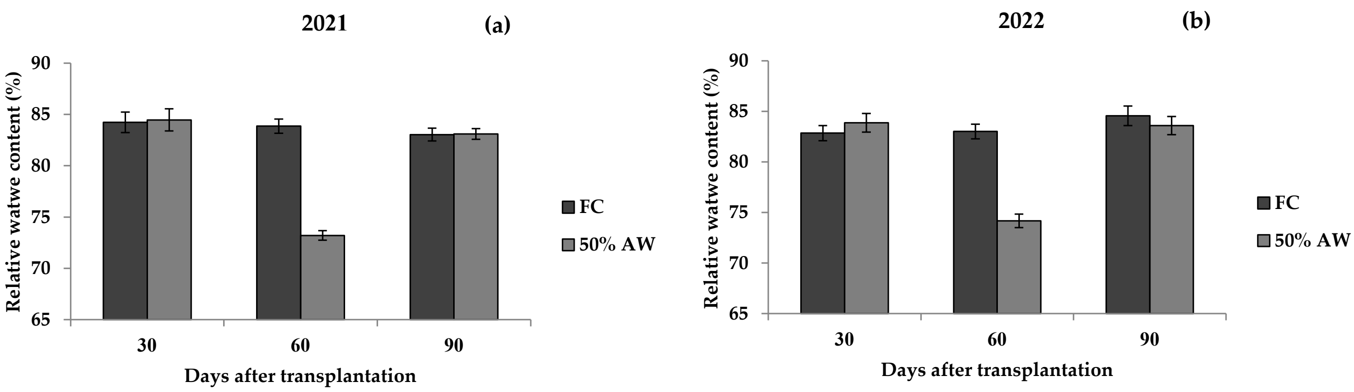

Figure 4. Percentages of relative water content (%) at 30, 60, and 90 days after transplanting in 2021 (**a**) and 2022 (**b**).

Visual observations revealed that the plants grown under 50% AW exhibited wilting during the afternoon between 31 and 60 DAT.

3.3. Combined Analysis of Variance

The effects of year (Y), water (W), and genotype (G) on shoot dry weight, root dry weight, tuber dry weight, biomass, harvest index, WUEt, and WUEb were highly significant ($p \leq 0.01$). Additionally, the interaction between year and genotype (Y × G) was significant for all traits (Table 2). However, the interaction between year and water (Y × W) was significant only for shoot dry weight. The interactions between water and genotype (W × G), as well as the higher-order interactions (Y × W × G), were significantly different for most traits, except for the harvest index. Therefore, the data from two years and different Jerusalem artichoke genotypes are presented separately for each water level.

Table 2. Mean squares for tuber dry weight, biomass, and harvest index of five Jerusalem artichoke genotypes grown under two water regimes: field capacity (FC) and mid-season drought (50% of available soil water, AW) in 2021 and 2022 growing seasons.

Source of Variance	df	Shoot Dry Weight (g/plant)	Root Dry Weight (g/plant)	Tuber Dry Weight (g/plant)	Biomass (g/plant)	Harvest Index	WUEt (g/l)	WUEb (g/l)
Year (Y)	1	693.8 ** (35.7)	98.6 ** (50.7)	489.1 ** (13.6)	3416.5 ** (31.6)	0.097 ** (15.2)	0.946 ** (34.0)	4.995 ** (55.3)
Rep within year	6	4.4 (1.4)	0.1 (0.3)	4.9 (0.8)	3.6 (0.2)	0.004 (4.1)	0.003 (0.6)	0.002 (0.6)
Water (W)	1	523.3 ** (26.9)	5.9 ** (3.1)	479.2 ** (13.3)	2219.7 ** (20.6)	0.022 ** (3.5)	0.110 ** (3.9)	0.646 ** (7.2)
Y × W	1	8.5 * (0.4)	0.1 ns (0.0)	1.3 ns (0.0)	17.9 ns (0.2)	0.002 ns (0.3)	0.001 ns (0.0)	0.0.12ns (0.1)
Genotype (G)	4	77.4 ** (15.9)	15.1 ** (31.1)	75.6 ** (8.4)	400.6 ** (14.8)	0.009 ** (5.9)	0.045 ** (6.4)	0.258 ** (11.4)
Y × G	4	20.9 ** (4.3)	2.4 ** (5.0)	460.6 ** (51.2)	543.0 ** (20.1)	0.082 ** (51.3)	0.303 ** (43.6)	0.350 ** (15.5)
W × G	4	37.0 ** (7.6)	2.1 ** (4.3)	38.8 ** (4.3)	171.5 ** (6.4)	0.006 ns (3.8)	0.027 ** (3.9)	0.117 ** (5.2)
Y × W × G	4	14.4 ** (3.0)	0.5 * (1.1)	29.7 ** (3.3)	83.5 ** (3.1)	0.004 ns (2.3)	0.017 ** (2.5)	0.055 ** (2.4)
Error	54	1.7 (4.8)	0.2 (4.4)	3.4 (5.1)	6.1 (3.0)	0.002 (13.6)	0.003 (4.9)	0.005 (2.7)
Total	79							

The numbers in parentheses represent the percentage (%) of the sum of squares relative to the total sum of squares. ns, *, ** non-significant, significant, and highly significant at $p \leq 0.05$ and $p \leq 0.01$ probability levels, respectively.

Year (Y) contributed substantially to the total variation in shoot dry weight (35.7%), root dry weight (50.7%), biomass (31.6%), WUEt (34.0%), and WUEb (55.3%). Water (W) had a lesser impact on the total variation in shoot dry weight (26.9%) and biomass (20.6%), highlighting the importance of irrigation management for optimizing these traits. Genotype (G) accounted for smaller variations in shoot dry weight (15.9%), root dry weight (31.1%), tuber dry weight (8.4%), biomass (14.8%), harvest index (5.9%), WUEt (6.4%), and WUEb (11.4%). The interaction between year and genotype (Y × G) contributed significantly to the variation in tuber dry weight (51.2%), harvest index (51.3%), and WUEt (43.6%).

In contrast, the interaction effects accounted for smaller portions of the total variation in shoot dry weight, root dry weight, tuber dry weight, biomass, harvest index, WUEt, and WUEb. These ranged from 0.0% to 0.4% for the interaction between year and water (Y × W), 3.8% to 7.6% for the interaction between water and genotype (W × G), and 1.1% to 3.3% for the higher-order interaction (Y × W × G).

3.4. The Effects of Mid-Season Drought Stress on Tuber Dry Weight, Biomass, and Harvest Index

Mid-season drought significantly reduced the tuber dry weight, biomass, harvest index, and both WUEt and WUEb of Jerusalem artichoke in both years (Table 3). In 2021, the average tuber dry weight under fully irrigated (FC) and mid-season drought conditions was 22.7 g/plant and 17.6 g/plant, respectively (Table 3). Mid-season drought at 50% available water (50% AW) reduced the tuber dry weight by an average of 19.9%. Significant differences were found among Jerusalem artichoke genotypes for tuber dry weight under both water regimes ($p \leq 0.01$). The tuber dry weight ranged from 15.5 to 35.5 g/plant under FC and from 13.3 to 21.7 g/plant under mid-season drought (Table 3), with reductions ranging from 5.8% to 38.4%, which were statistically significant.

Table 3. Tuber dry weight, biomass, and harvest index, along with their respective reductions of five Jerusalem artichoke genotypes under two water regimes: field capacity (FC) and mid-season drought (50% of available soil water, AW) in the 2021 and 2022 growing seasons.

Genotypes	Tuber Dry Weight (g/plant)		Reduction (%)	Biomass (g/plant)		Reduction (%)	Harvest Index		Reduction (%)	WUEt (g/L)		WUEb (g/L)	
	FC	50% AW	50% AW	FC	50% AW	50% AW	FC	50% AW	50% AW	FC	50% AW	FC	50% AW
CN 52867	20.9 b	13.6 b	35.1 a	40.3 c	27.6 d	31.1 b	0.52 c	0.48 b	7.4 a	0.56 b	0.41 b	1.09 c	0.84 d
JA 125	35.5 a	21.7 a	38.4 a	61.6 a	33.8 b	45.1 a	0.58 b	0.64 a	−11.9 b	0.96 a	0.66 a	1.67 a	1.02 b
JA 15	15.5 c	13.3 b	14.4 b	36.1 d	28.0 cd	22.3 b	0.43 d	0.48 b	−10.5 b	0.42 c	0.41 b	0.98 d	0.85 cd
JA 3	21.4 b	20.1 a	5.8 b	35.2 d	32.8 bc	7.7 c	0.61 a	0.61 a	−3.6 b	0.58 b	0.61 a	0.95 d	0.99 bc
JA 89	20.4 b	19.2 a	5.8 b	47.2 b	40.9 a	19.4 bc	0.43 d	0.47 b	−5.2 b	0.55 b	0.58 a	1.28 b	1.24 a
Means	22.7	17.6	19.9	44.1	32.6	25.1	0.51	0.54	−4.8	0.61	0.53	1.19	0.99
F-test	**	**	**	**	**	**	**	**	**	**	**	**	**
CN 52867	24.5 a	17.9 a	26.3 b	37.4 b	25.4 ab	31.6 b	0.65 a	0.71a	−7.7 ab	0.55 a	0.45 a	0.83 b	0.64 ab
JA 125	10.1 c	5.7 d	43.4 a	21.9 d	10.0 d	54.0 a	0.46 c	0.56bc	−22.4 c	0.22 c	0.14 d	0.49 d	0.25 d
JA 15	19.5 b	15.0 b	23.4 b	29.8 c	23.5 b	21.0 c	0.66 a	0.64ab	2.9 a	0.44 b	0.38 b	0.66 c	0.59 b
JA 3	10.0 c	8.8 c	12.5 b	18.6 d	16.7 c	7.8 d	0.54 b	0.53c	3.5 a	0.22 c	0.22 c	0.41 d	0.43 c
JA 89	23.6 a	17.3 a	26.5 b	42.7 a	26.8a	37.2 b	0.55 b	0.65ab	−16.9 bc	0.52 a	0.43 a	0.95 a	0.67 a
Means	17.5	12.9	26.4	30.1	20.5	30.3	0.55	0.59	−8.1	0.39	0.32	0.67	0.51
F-test	**	**	*	**	**	**	**	**	**	**	**	**	**

Means followed by different lowercase letters within the same column are significantly different based on the LSD test at $p \leq 0.05$. * and ** indicate significant and highly significant at $p \leq 0.05$ and $p \leq 0.01$ probability levels, respectively.

For biomass, the overall means under FC and mid-season drought were 44.1 g/plant and 32.6 g/plant, respectively (Table 3). Mid-season drought reduced the biomass by an average of 25.1%. Significant genotype differences for biomass were also observed under both water regimes ($p \leq 0.01$). Biomass ranged from 35.2 to 61.6 g/plant under FC and from 27.6 to 40.9 g/plant under mid-season drought (Table 3).

The harvest index showed an overall mean of 0.51 under FC and 0.54 under mid-season drought (Table 3), with an average increase of 4.8% under drought. Significant genotype differences were noted for the harvest index under both water regimes ($p \leq 0.01$). The harvest index ranged from 0.43 to 0.61 under FC and from 0.47 to 0.64 under mid-season drought (Table 3).

Mid-season drought also reduced both WUEt and WUEb (Table 3). On average, mid-season drought reduced WUEt by 13.1% and WUEb by 16.8%. Significant differences were observed among genotypes for both WUEt and WUEb under both water regimes ($p \leq 0.01$). WUEt ranged from 0.42 to 0.96 g/liter under FC and from 0.41 to 0.66 g/liter under mid-season drought. WUEb ranged from 0.95 to 1.67 g/liter under FC and from 0.84 to 1.24 g/liter under mid-season drought.

Genotypic differences in response to mid-season drought were particularly pronounced in 2021 (Table 3). CN 52867 exhibited substantial reductions in tuber dry weight, biomass, and harvest index, coupled with low water-use efficiency (WUEt and WUEb). In contrast, JA 125 showed similar reductions in tuber dry weight and biomass but displayed higher WUEt and WUEb. JA 15 showed resilience with minimal reductions in tuber dry weight and harvest index but had lower WUEt and WUEb. Finally, JA 3 and JA 89 demonstrated strong drought tolerance, exhibiting minimal reductions in tuber dry weight, biomass, and harvest index, while maintaining high WUEt and WUEb.

In 2022, the overall means for tuber dry weight under FC and mid-season drought were 17.5 g/plant and 12.9 g/plant, respectively (Table 3). Mid-season drought stress reduced the tuber dry weight by an average of 26.4%. Significant differences were again observed among genotypes for tuber dry weight under both water regimes ($p \leq 0.01$). The tuber dry weight ranged from 10.0 to 24.5 g/plant under FC and from 5.7 to 17.9 g/plant under mid-season drought (Table 3), with reductions ranging from 12.5% to 43.4%.

For biomass in 2022, the overall means under FC and mid-season drought were 30.1 g/plant and 20.5 g/plant, respectively (Table 3). Mid-season drought reduced biomass by 30.3%. Significant genotype differences for biomass were observed under both water regimes ($p \leq 0.01$), with biomass values ranging from 18.6 to 42.7 g/plant under FC and from 10.0 to 26.8 g/plant under mid-season drought (Table 3).

The harvest index in 2022 showed overall means of 0.55 under FC and 0.59 under mid-season drought (Table 3), with an average increase of 6.8% under drought. Significant differences were found among genotypes for the harvest index under both water regimes ($p \leq 0.01$).

Mid-season drought reduced both WUEt and WUEb in 2022 (Table 3). On average, the WUEt was reduced by 17.9% and the WUEb by 23.9%. Significant differences among genotypes for both WUEt and WUEb were observed under both water regimes ($p \leq 0.01$). The WUEt values ranged from 0.22 to 0.55 g/liter under FC and from 0.14 to 0.45 g/liter under mid-season drought. The WUEb values ranged from 0.41 to 0.95 g/liter under FC and from 0.25 to 0.67 g/liter under mid-season drought.

Genotypic variability was evident for tuber dry weight, biomass, harvest index, WUEt, and WUEb in 2022, under both fully irrigated (FC) and mid-season drought conditions (Table 3). CN 52867 and JA 89 consistently exhibited high tuber dry weights and biomass across both water regimes, although they experienced substantial reductions under mid-season drought. JA 15 demonstrated moderate tuber dry weight and biomass, with a moderate decrease under drought. In contrast, JA 125 and JA 3 consistently produced lower tuber dry weights and biomass, with JA 125 showing a particularly pronounced reduction. The harvest index was highest in CN 52867 and JA 15, with CN 52867 showing an increase under mid-season drought. JA 3 and JA 89 exhibited relatively low harvest indices, while JA 125, despite having low harvest indices, experienced an increase under drought. In terms of water-use efficiency (WUEt and WUEb), CN 52867 and JA 89 consistently showed high values, while JA 15 exhibited moderate levels. JA 125 and JA 3 exhibited low WUEt and WUEb across both water regimes.

4. Discussion

Previous research on the effects of water stress on Jerusalem artichoke tuber yield and biomass has been conducted in temperate and tropical regions [6–8,10,11,16,22,23]. However, these studies have not specifically examined the impact of mid-season drought on yield and water-use efficiency (WUE) in Jerusalem artichoke genotypes with varying levels of drought resistance. This study aimed to evaluate the responses of different genotypes to mid-season drought, focusing on tuber yield, biomass, and WUE.

The interaction between year and genotype (Y × G) was highly significant for all traits, and the secondary-level interaction (Y × W × G) was significant for most traits, except the harvest index. These findings suggest that genotype responses to mid-season drought vary across years, influenced by climatic factors and environmental conditions.

Year-specific differences were observed for shoot dry weight, root dry weight, biomass, WUEt, and WUEb. In 2021, the tuber dry weight, biomass, WUEt, and WUEb were higher than in 2022, while the harvest index was greater in 2022. Environmental factors, particularly higher air temperatures in 2021, contributed to these differences. The increased relative humidity in 2021 facilitated better establishment during the primary growth stage, but it also reduced growth and yield, negatively affecting the harvest index.

In regions with high temperatures, Jerusalem artichoke planting often results in decreased individual tuber dry weight and increased tuber numbers per plant [24]. To optimize production in tropical regions, Jerusalem artichoke should be evaluated under dry-season, low-temperature conditions. Studies on potatoes have shown similar trends, in which high temperatures reduce the photosynthate allocation to individual tubers [25]. Cooler temperatures may increase dry matter accumulation in the tubers, improving economic yield productivity. Moreover, lower temperatures in the second year could slow evapotranspiration, mitigating water deficits [26].

The genotype effects were significant for all traits. This indicates the potential to select Jerusalem artichoke genotypes for traits such as tuber yield, biomass, harvest index, WUEt, and WUEb in tropical areas. Interactions between water regimes and genotypes (W × G) were also significant across both years, highlighting differential genotype responses to water stress.

Mid-season drought stress significantly reduced the tuber dry weight. In temperate regions, mid-season drought during tuber initiation had a pronounced negative impact on yield [6]. This underscores the importance of well-timed irrigation strategies during critical growth phases. Interestingly, mid-season drought elevated the harvest index in most genotypes by reducing shoot growth and directing assimilates to the tubers. This aligns with findings in sweet potatoes [27] but contrasts with studies reporting no impact or a reduced harvest index under long-term drought conditions [6,10,11].

The water-use efficiency (WUEt and WUEb) declined under mid-season drought, consistent with previous studies [9,11]. However, variations in WUE responses, as reported by Conde et al. [6], may be attributed to differences in genotype, stress intensity, and air temperature.

Genotype-specific analyses revealed that JA 125, JA 3, JA 89, and CN 52867 demonstrated high tuber dry weight potential in 2021, while JA 89 and CN 52867 maintained superior performance in 2022. Based on the yield and yield-reduction patterns, the genotypes were classified into three groups: (1) high yield potential and significant yield reduction: CN 52867, JA 125 (2021) and CN 52867, JA 89 (2022); (2) high yield potential and low yield reduction: JA 3, JA 89 (2021); (3) low yield potential and low yield reduction: JA 15, JA 3 (2022). These findings suggest that CN 52867 and JA 89 are promising candidates for high-yield genotypes, while JA 3 shows resilience under mid-season drought stress.

Based on the findings of this study, future research should focus on exploring the physiological mechanisms underlying drought tolerance in Jerusalem artichoke, particularly in genotypes such as CN 52867, JA 89, and JA 3 under field condition. Focusing on the root and physiological parameters, along with genotype × environment interactions, will be essential for identifying traits that enhance drought resilience. Furthermore, breeding programs should aim to integrate drought tolerance with high yield potential, and studies on the long-term effects of drought and sustainable water management will contribute to optimizing crop productivity in water-scarce regions.

5. Conclusions

Mid-season drought reduced the tuber dry weight, biomass, WUEt, and WUEb but increased the harvest index. Significant differences among Jerusalem artichoke genotypes were observed for tuber dry weight, biomass, harvest index, WUEt, and WUEb under both field capacity (FC) and mid-season drought conditions. Based on their responses to mid-season drought in terms of tuber dry weight, the genotypes were classified into two groups. CN 52867 and JA 89 fell into the group with high water-use efficiency (WUE), high yield potential, and substantial yield reduction. In contrast, JA 3 was classified in the group with low yield reduction. These findings provide valuable information for selecting Jerusalem artichoke genotypes and suggest that the two genotype groups could serve as parental lines for breeding new varieties with high yield potential and enhanced drought tolerance for regions prone to mid-season drought.

Author Contributions: Conceptualization, R.R. and S.J.; methodology, R.R. and R.P.; software, R.R. and C.A.; validation, R.R., S.J. and C.A.; formal analysis, R.R. and A.J.; investigation, T.K.-N. and R.R.; resources, S.J. and R.P.; data curation, R.R. and C.A.; writing—original draft preparation, R.R.; writing—review and editing, R.R.; visualization, R.R.; supervision, S.J.; project administration, R.R.; funding acquisition, R.R. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially supported by the Office of the Permanent Secretary, Ministry of Higher Education, Science, Research, and Innovation (Grant No. RGNS 63-109).

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments: We express our sincere gratitude to the Faculty of Agriculture and Technology, Rajamangala University of Technology Isan, Surin Campus, Surin, Thailand, for providing laboratory space and research facilities. Additionally, we would like to acknowledge Mr. Abil Dermail for his meticulous proofreading of the manuscript.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

WUEt	Tuber water-use efficiency
WUEb	Biomass water-use efficiency
FC	Field capacity
50% AW	50% available soil water
DAT	Days after transplanting
RWC	Relative water content
WUE	Water-use efficiency
ANOVA	Analysis of variance
RCBD	Randomized complete block design
LSD	Least significant difference

References

1. Kays, S.J.; Nottingham, S.F. *Biology and Chemistry of Jerusalem Artichoke: Helianthus tuberosus* L.; CRC Press: Boca Raton, FL, USA, 2007.
2. Barclay, T.; Ginic-Markovic, M.; Coope, P.; Petrovsky, N. Inulin-a versatile polysaccharide with multiple pharmaceutical and food chemical uses. *J. Excip. Food Chem.* **2010**, *1*, 27–50.
3. Yang, M.J.; Wang, L.; Wu, J.; Li, Z.Z. Study on antioxidant activity of flavonoids from *Helianthus tuberosus* leaves in vitro. *Guizhou Agric. Sci.* **2011**, *4*, 52–54.
4. Pan, L.; Sinden, M.R.; Kennedy, A.H.; Chai, H.; Watson, L.E.; Graham, T.L.; Kinghorn, A.D. Bioactive constituents of *Helianthus tuberosus* (Jerusalem artichoke). *Phytochem. Lett.* **2009**, *2*, 15–18. https://doi.org/10.1016/j.phytol.2008.10.003.
5. Cepl, J.; Kasal, P.; Souckova, H.; Svobodova, A.; Bucher, P. Non-food production of Jerusalem artichoke (*Helianthus tuberosus*) and possibilities of its energetic utilization. *Actual Tasks Agric. Eng.* **2012**, *40*, 517–526.
6. Conde, J.R.; Tenorio, J.L.; Rodriguez-Maribona, B.; Ayerbe, L. Tuber yield of Jerusalem artichoke (*Helianthus tuberosus* L.) in relation to water stress. *Biomass Bioenergy* **1991**, *1*, 137–142. https://doi.org/10.1016/0961-953490022-5.
7. Losavio, N.; Lamascese, N.; Vonella, A.V. Water requirements and nitrogen fertilization in Jerusalem artichoke (*Helianthus tuberosus* L.) grown under Mediterranean conditions. *Acta Hortic.* **1997**, *449*, 205–209. https://doi.org/10.17660/ActaHortic.1997.449.28.
8. Ruttanaprasert, R.; Poramate, B.; Jogloy, S.; Vorasoot, N.; Kesmala, T.; Kanwar, R.S.; Holbrook, C.C.; Patanothai, A. Genotypic variability for tuber yield, biomass and drought tolerance in Jerusalem artichoke germplasm. *Turk. J. Agric. For.* **2014**, *38*, 570–580. https://doi.org/10.3906/tar-1310-43.

9. Janket, A.; Jogloy, S.; Vorasoot, N.; Kesmala, T.; Holbrook, C.C.; Patanothai, A. Genetic diversity of water use efficiency in Jerusalem artichoke (*Helianthus tuberosus* L.) germplasm. *Aust. J. Crop Sci.* **2013**, *7*, 1670–1681.
10. Chaimala, A.; Jogloy, S.; Vorasoot, N.; Toomsan, B.; Jongrungklang, N.; Kesmala, T.; Holbrook, C.C.; Kvien, C. Responses of total biomass, shoot dry weight, yield and yield components of Jerusalem artichoke (*Helianthus tuberosus* L.) varieties under different terminal drought duration. *Agriculture* **2020**, *10*, 198. https://doi.org/10.3390/agriculture10060198.
11. Ruttanaprasert, R.; Jogloy, S.; Vorasoot, N.; Kesmala, T.; Kanwar, R.; Holbrook, C.; Patanothai, A. Effects of Water Stress on Total Biomass, Tuber Yield, Harvest Index, and Water Use Efficiency in Jerusalem Artichoke. *Agric. Water Manag.* **2016**, *166*, 130–138. https://doi.org/10.1016/j.agwat.2015.12.022.
12. Ruttanaprasert, R.; Jogloy, S.; Vorasoot, N.; Kesmala, T.; Kanwar, R. S.; Holbrook, C. C.; Patanothai, A. Root Responses of Jerusalem Artichoke Genotypes to Different Water Regimes. *Biomass Bioenergy* **2015**, *81*, 369–377. https://doi.org/10.1016/J.BIOMBIOE.2015.07.027.
13. Chaimala, A.; Jogloy, S.; Vorasoot, N.; Holbrook, C.; Kvien, C. The roles of net photosynthetic rate and transpiration efficiency on economic yield of Jerusalem artichoke (*Helianthus tuberosus* L.) genotypes under different drought durations during the terminal growth stages. *Agronomy* **2023**, *13*, 1882. https://doi.org/10.3390/agronomy13071882.
14. Doorenbos, J.; Pruitt, W.O. Calculation of crop water requirements. In *Guideline for Predicting Crop Water Requirement FAO Irrigation and Drainage Paper No. 24*; FAO: Rome, Italy, 1992; pp. 1–65.
15. Singh, S.; Russell, M.B. Water Use by Maize/Pigeon Peas Intercrop on A Deep Vertisol. In Proceedings of the International Workshop on Pigeonpeas, ICRISAT Center Patancheru, Andhra Pradesh, India, 15–19 December 1980; Volume 1.
16. Monti, A.; Amaducci, M.T.; Venturi, G. Growth response, leaf gas exchange and fructans accumulation of Jerusalem artichoke (*Helianthus tuberosus* L.) as affected by different water regimes. *Eur. J. Agron.* **2005**, *23*, 136–145. https://doi.org/10.1016/j.eja.2004.11.001.
17. Google. Map Directions from Rajamangala University of Technology Isan, Surin Campus, Surin, Thailand. Google Maps. Available online: https://www.google.com/maps (accessed on 29 January 2025).
18. Kramer, P.J. Drought, stress and the origin of adaptation. In *Adaptation of Plant to Water and High Temperature Stress*; Turner, N.C., Kramer, P.J., Eds.; John Wiley and Sons: New York, NY, USA, 1980; pp. 7–20.
19. Teare, I.D.; Sionit, N.; Kramer, P.J. Change in water status during water stress at different stages of development in wheat. *Physiol. Plant.* **1982**, *55*, 296–300. https://doi.org/10.1111/j.1399-3054.1982.tb00295.x.
20. Gomez, K.A.; Gomez, A.A. *Statistical Procedure for Agricultural Research*; John Wiley and Sons: Singapore, 1984; pp. 594–600.
21. Statistix, 8. *Statistix 8: Analytical Software User's Manual*; Analytical Software: Tallahassee, FL, USA, 2003.
22. Schittenhelm, S. Agronomic performance of root chicory, Jerusalem artichoke and sugar beet in stress and non-stress environment. *Crop Sci.* **1999**, *39*, 1815–1823. https://doi.org10.2135/cropsci1999.3961815x.
23. Liu, Z.X.; Spiertz, J.H.J.; Jing, S.; Shuai, X.; Guang, H.X. Growth and yield performance of Jerusalem artichoke clones in a semiarid region of China. *Agron. J.* **2012**, *104*, 1538–1546. https://doi.org/10.2134/agronj2012.0091.
24. Ruttanaprasert, R.; Jogloy, S.; Vorasoot, N.; Kesmala, T.; Kanwar, R.S.; Holbrook, C.C.; Patanothai, A. Photoperiod and growing degree days effect dry matter partitioning in Jerusalem artichoke. *Int. J. Plant Prod.* **2013**, *7*, 393–416.
25. Ewing, E.E.; Sandlan, K.P. Biomass partitioning in the potato: Considerations for modeling. In *Modelling and Parameterization of The Soil-Plant-Atmosphere System: A Comparison of Potato Growth Models*; Kabat, P., Marshall, B., van den Broek, B.J., Vos, J., van Keulen, H., Eds.; Wageningen Pers: The Hague, The Netherlands, 1995.
26. Denmead, O.T.; Shaw, R.H. Availability of soil water to plants as affected by soil moisture content and meteorological conditions. *Agron. J.* **1962**, *54*, 385–390. https://doi.org/10.2134/agronj1962.00021962005400050005x.
27. Makunde, G.; Andrade, M.; Ricardo, J.; Alvaro, A.; Menomussanga, J.; Grüneberg, W. Adaptation to mid-season drought in a sweet potato (*Ipomoea batatas* [L.] Lam) germplasm collection grown in Mozambique. *Open Agric.* **2017**, *2*, 133–138. https://doi.org/10.1515/opag-2017-0012.