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Genotype by Environment (G×E) Interactions for Yield Components of Jerusalem Artichoke (*Helianthus tuberosus* L.)

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Abstract: Inulin containing tubers of Jerusalem artichoke (*Helianthus tuberosus* L.) can be used as raw material for healthy products, sweeteners, bio-ethanol and animal feed. The objective of this study was to evaluate the effects of cultivar, environment and cultivar×environment interaction on fresh tuber yield tuber number and tuber size of Jerusalem artichoke. Fifteen cultivars were evaluated in a randomized complete block design with four replications at nine environments in the Northeast of Thailand. Differences among cultivars were observed for fresh tuber yield, tuber number and weight of individual tubers (tuber size). Environment effect contributed to a larger portion of variations in fresh tuber yield, tuber number and tuber size. Although, genotype× environment interactions were also significant, their values were much smaller than genotype main effects for all characters. Stability parameters indicated that exploitation of superior cultivars with adaptation to a wide range of environments and the cultivars with specific adaptation to specific environments would be possible. Low correlation but significant was found for fresh tuber yield and tuber number, indicating that tuber yield in some cultivars was dependent on high tuber number. Strong correlation between fresh tuber yield and tuber size indicated that bigger tuber is necessary to obtain higher tuber yield. Negative but significant correlation between tuber number and tuber size indicated that increased tuber size is on the expense of tuber number. JA 89 was the most promising cultivar for wide adaptation and high tuber yield, whereas HEL 65 was the most promising cultivar for its bigger tubers and acceptable yield.

Key words: Cultivar, inulin, stability parameter, tuber number, tuber yield

INTRODUCTION

Among species in *Helianthus* genus, only two species has been exploited in agriculture. Sun flower (*Helianthus annuus* L.) is cultivated for seed oil, while tubers of Jerusalem artichoke (*Helianthus tuberosus* L.) are consumed (Heiser, 1978). Originated in the temperate climate of North America, Jerusalem artichoke has been introduced into different climates such as tropics. As Jerusalem artichoke tuber is rich in carbohydrate in form of inulin (Ge and Zhang, 2005). It is consumed as vegetable and used as raw material for making a variety of products including bio-ethanol, high fructose syrup, healthy food products and animal feed (Monti *et al*., 2005; Yildiz *et al*., 2006). Jerusalem artichoke is suggested to be perspective prebiotic fructan-containing additive for fermented synbiotic milks or oat-hydrolysate based products (Semjonovs *et al*., 2007). Jerusalem artichoke was previously considered to be underutilized crop. In the past, it served as food for indigenous people and the new settlers. It is also known as potato for the poor. At the present, Jerusalem artichoke is considered as a new crop with high potential to serve several purposes. Jerusalem artichoke now attracts the attentions of agronomists and breeders to improve its productivity in order that the production of Jerusalem artichoke will be viable and profitable in commercial scale in both temperate and tropical environments with or without irrigation.

In temperate regions of the North biosphere where Jerusalem artichoke is originated, it is grown during frost free period that can be less than 85 days to more than 125 days (Cosgrove *et al*., 1991). Most varieties require at least 125 days of frost free period and the tubers are harvest after frost. In these regions, frost free period can limit yield because late maturing cultivars will never flower (Denoroy, 1996). In the United States, Jerusalem artichoke well adapt in the upper two third of the country and it does not adapt in the third lower part of the country (Yungen, 1992).

In the tropics where frost is not a problem, drought can limit its production especially in the dry season if irrigation is not available. Although irrigation is available,

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Jerusalem artichoke varieties may respond differently to environmental factors such as soil type, alleviation, temperature, fertility and management (Kays and Nottingham, 2008). The extent to which the genotypes respond can be low that the genotype×environment (G×E) effect can be ignored or high that the identification of superior genotypes is difficult. In case of low G×E interaction, the best genotypes can be recommended for cultivation across a wide range of environments. If the interaction is high, specific genotypes should be recommended for specific environments. This information is very important for the recommendation of new varieties and the information is not available for Jerusalem artichoke grown under tropical climates with supplemental irrigation.

The objective of this study was to evaluate the effects of cultivar, environment and cultivar×environment interaction on fresh tuber yield tuber number and tuber size of Jerusalem artichoke grown under rainfed conditions with supplemental irrigation in the Northeast of Thailand.

MATERIALS AND METHODS

The 118 Jerusalem artichoke accessions kindly donated from two institutions were primarily evaluated at the Khon Kaen University (KKU) Agronomy Farm in 2004. These included 103 accessions from the plant genetic resources of Canada at Saskatoon Research Centre and 15 genotypes from the Leibniz Institute of Plant Genetics and Crop Plant Research of Germany. The evaluation resulted in the selection of 14 top yielding clones. The KKU Ac 001 is a first introduced clone in Thailand with unknown origin and it was used as a standard check. In this study, KKU Ac 001 and other 14 promising accessions (Table 1) were evaluated in nine environments (Table 2). Seven environments were conducted at the KKU farm (16° 28' 31.60" N, 102° 48' 30.29" E), one environment was conducted at the research farm of Rajabhat University, Udon Thani Province (17° 21' 06.32" N, 102° 48' 42.92" E), one environment was conducted at the highland research Farm of Khon Kaen University located at Chulaporn dam, Chaiyaphum Province (16° 31' 53.19" N, 101° 38' 03.21" E). Although, most trials were conducted at KKU site, they were conducted in different fields seasons and years. The growing seasons were early rainy, late rainy and dry with varying planting dates.

Sprouted seed tubers were used as planting materials. To prepare the sprouted seed tubers, the tubers were cut into small pieces each of which had at least three buds. Moistened lime was used to heal the cut wound and reduce tuber rot. The tuber pieces were incubated in plastic trays containing moistened coconut outer husk (coconut peat) at the bottom and the top of the trays under ambient conditions for 3-4 days in the warmer season and 4-7 days in colder season. The tuber pieces with active buds and roots were further transferred to plug plastic trays for germination. Each tray had 104 cone-shaped cells containing a mixture of 1/1 soil/burnt rice husk medium for 7 days. The pre-sprouted seedlings were then suitable for transplanting in the fields.

The trials were conducted during 2005 to 2008. A randomized complete block design with four replications was used for each environment. The fields were primarily disc-ploughed one time and secondary plough was done twice. Lime at the rate of 625 kg ha^{-1} was incorporated into the soil at the last plough. In each replication, the Jerusalem artichoke cultivars were planted in plots with six rows each of which had 5 m in length and a spacing of 50×50 cm between rows and between hills within row

Table 1: Genotypes and sources of origin

Genotype	Country of origin[1]	Donation institutes
JA 37	Canada	PGRC, Canada
JA 38	Canada	PGRC, Canada
JA 67	USA	PGRC, Canada
JA 89	France	PGRC, Canada
HEL 53	Germany	IPK, Germany
JA 102	Germany	PGRC, Canada
HEL 335	Na	IPK, Germany
HEL 231	Germany	IPK, Germany
HEL 69	Na	IPK, Germany
HEL 61	Russia	IPK, Germany
HEL 65	Russia	IPK, Germany
HEL 68	Na	IPK, Germany
HEL 66	Ukraine	IPK, Germany
CN 52867	Russia	PGRC, Canada
KKU Ac 001	Na	Na

[1]Kay and Nottingham (2008), Na: Not available, PGRC: Plant Gene Resources of Canada, IPK: Leibniz Institute of Plant Genetics and Crop Plant Research

Table 2: Brief description of locations where the trials were planted

Environment	Growing period	Altitudes (m)	Accumulated rain (mm)	Max/Min temperature	Soil type
KKU farm (E1)	Jun-Sep 2005	190	765.9	32.5/24.7	Loamy sand
KKU farm (E2)	Mar-Jun 2006	190	524.6	34.5/24.8	Loamy sand
KKU farm (E3)	Sep-Dec 2006	190	280.5	32.1/22.1	Loamy sand
KKU farm (E4)	Jun-Sep 2007	190	839.3	33.0/25.4	Loamy sand
KKU farm (E5)	Mar-Jun 2007	190	652.9	33.6/24.5	Loamy sand
Udon Thani (E6)	Mar-Jun 2007	200	782.7	36.9/19.9	Sandy loam
Chaiyaphum (E7)	Apr-Jun 2007	800	529.8	29.3/19.7	Loamy clay
KKU farm (E8)	Jul-Oct 2008	190	1027.9	32.0/25.1	Loamy sand
KKU farm (E9)	Oct 2008-Jan 2009	190	170.3	29.9/19.9	Loamy sand

which resulted in the population density of 40,000 plants ha^{-1}. The population density was larger than 40,000 stems ha^{-1} because seed tubers could germinate 1-5 stems. The cultivars were planted in flat soil without soil ridge. Water channels were created around each replication to drain excessive water. Mini sprinkler system was installed to supply necessary water to the experiment.

Shortly prior to planting, the soil was moistened and the sprouted seed tubers were planted at a depth of 5 cm between 8.00 to 12.00 h in the morning to avoid severe wilting of the seedlings. Regular irrigation was carried out from planting until crop establishment. Re-planting of died plants was done within a week after transplanting, using sprouted seed tubers with similar age.

Manual weed control was carried at 14 days after transplanting. Combination of N-P_2O_5-K_2O fertilizers (15-15-15) at the rate of 156.25 kg ha^{-1} was applied at 30 days after transplanting. After fertilization, any operation was not necessary except for irrigation if soil moisture was not enough or the plants showed apparent wilting. No pesticide or insecticide was applied throughout the crop. Harvest was done between 80 to 125 days after planting depending on genotypes.

Maturity could be determined by defoliation and total senescence of the above ground stems and the stems turned yellowish to brown. At maturity, five plants in each plot were sampled randomly, uprooted and the stems were cut at the crowns. Roots were discarded. The samples were used to record tuber number and weight of individual tubers (tuber size). As tubers of Jerusalem artichoke have chain growth habit, producing secondary and tertiary tubers, only primary tubers that attach to the crown were considered and counted and the stolons were separated from the tubers. To determine yield, the plants at the ends of the rows were discarded and all plants in the plot with harvest area of 9 m^2 were counted and harvested. Tubers were dug with hoes and soil debris was removed, then tuber fresh weight was determined.

Statistical analysis: Data of tuber yield, tuber number and tuber size for each environment were subjected to analysis of variance, using the SAS computer program (SAS, 2001). Error variances were tested for homogeneity (Gomez and Gomez, 1984) and neither of the characters showed heterogeneous variance. Then, data across environments were combined and analyzed statistically according to a statistical model as follows (Freeman, 1973);

$$Y_{ijk} = \mu+E_k+R_{j/k}+T_i+(E\times T)_{ik}+\epsilon_{ijk}$$

Where:

Y_{ijk} = Yield of cultivar i in replication j in environment k
i = Rank of cultivar 1, 2, 3,…, v
j = Rank of replication 1, 2, 3,…, r
k = Rank of environment 1, 2, 3,…, n
μ = Mean yield across the whole experiment for all cultivar and location
E_k = Effect of environment k
T_i = Effect of cultivar i
$R_{j/k}$ = Effect of replication j in environment k
$(E\times T)_{ik}$ = Effect of interaction among cultivar i and environment k
ϵ_{ijk} = Error of cultivar i replication j in environment k

For environment and genotype main effects where they were statistically significant, LSDs were calculated to compare mean differences. Where genotype× environment effects were significant, stability parameters were calculated, using the method described by Eberhart and Russell (1966) and the stability parameters were tested for their differences from 1.

Standard Deviations (SD) for stability parameters were also calculated and tested for their differences from 0. Therefore, stability for each character of each genotype could be determined, using means, stability parameters and standard deviations of stability parameters. Simple correlation coefficients among tuber yield, tuber number and tuber size were also calculated, using correlation function in Microsoft Excel.

RESULTS

It is clear that environment contributed to the large portion of variations in tuber fresh weight, tuber number and tuber size, whereas genotype contributed a smaller portion to variations in all studied traits (Table 3). The variations in these characters as affected by genotypic differences were significant and much smaller than the variations caused by environmental differences. The contributions of genotype×environment interactions to the differences in tuber fresh weight, tuber number and tuber size were significant for all characters but much smaller than those caused by genotypic differences. The significant G×E interactions indicated that selection of

Table 3: Mean squares for tuber fresh weight, tuber No. plant^{-1} and weight of individual tubers of 15 Jerusalem artichoke clones evaluated at 9 environments during 2005-2008

SOV	df	Tuber fresh weight	Tuber No. plant^{-1}	Weight of individual tubers
Environment (E)	8	2686.5**	2537.0**	152868**
Rep/E	27	36.2	100.3	1621
Genotypes (G)	14	165.9**	1642.0**	15529**
G×E	112	55.9**	151.2**	3930**
Pooled error	378	13.7	58.4	1052
Total	539			
CV (%)		23.7	31.4	33.2

**Significant at 0.01 probability level

Table 4: Tuber fresh weight (t ha^{-1}) of 15 Jerusalem artichoke clones grown at 9 environments during 2005-2008

	Environment									
Genotype	E1	E2	E3	E4	E5	E6	E7	E8	E9	Genotype mean
JA 37	14.10	18.40	26.20	16.40	13.50	16.40	31.60	12.70	12.50	18.00
JA 38	11.40	15.70	21.60	17.80	14.10	12.00	29.70	7.10	8.40	15.30
JA 67	7.50	6.20	21.50	7.20	5.00	7.40	26.20	3.00	11.00	10.50
JA 89	15.80	18.20	23.70	14.50	19.30	8.80	33.60	17.20	19.40	18.90
HEL 53	9.10	8.20	36.00	11.80	16.00	14.60	23.50	14.00	19.70	17.00
JA 102	8.50	7.90	23.10	7.80	16.60	12.10	38.90	9.30	14.20	15.40
HEL 335	8.60	7.30	27.50	5.60	15.30	6.70	31.10	7.80	17.50	14.20
HEL 231	11.70	14.80	27.50	9.20	22.30	13.70	27.60	14.90	15.30	17.40
HLE 69	11.60	5.50	29.40	8.80	14.70	11.60	31.10	7.20	21.80	15.80
HEL 61	10.60	8.10	26.40	11.40	13.50	10.70	30.40	10.10	20.20	15.70
HEL 65	21.30	19.70	25.60	8.20	15.40	10.20	31.00	5.60	13.50	16.70
HEL 68	12.60	8.60	30.60	9.60	11.30	11.60	30.60	9.20	21.10	16.10
HEL 66	7.90	9.00	28.40	9.60	16.60	13.70	30.30	9.20	15.70	15.60
CN 52867	17.90	22.80	26.00	14.40	14.10	26.30	26.10	10.10	11.80	18.80
KKU Ac 001	8.00	4.70	26.80	12.70	16.90	16.00	33.10	9.30	13.20	15.60
Environmental mean	11.80	11.70	26.70	11.00	15.00	12.80	30.30	9.80	15.70	16.10
LSD	1.96	2.78	2.20	2.37	2.62	3.10	3.53	1.86	2.71	2.57

Environment identification: E1: KKU farm rainy season 2005, E2: KKU farm dry season 2006, E3: KKU farm dry season 2006, E4: KKU farm rainy season 2007, E5: KKU farm dry season 2007, E6: Udon Thani dry season 2007, E7: Chaiyaphum dry season 2007, E8: KKU farm rainy season 2008, E9: KKU farm dry season 2008

genotypes that adapted to specific environments is possible in this population and multi-environment trials are necessary to determine superior genotypes.

Fresh tuber yield: Significant variation in tuber yield across environment was observed, ranging between 3.0 and 38.9 t ha^{-1} with 16.1 t ha^{-1} for overall mean (Table 4). The lowest yield belonged to JA 67 at KKU Farm in the rainy season 2008 (3.0 t ha^{-1}) and the highest yield belonged to JA 102 at Chaiyaphum trial in the dry season 2007 (38.9 t ha^{-1}). However, cultivar means across environments were not much different, ranging from 10.5 to 18.9 t ha^{-1}. Top-yielding environments were the trail in Chaiyaphum province (30.3 t ha^{-1}) followed by the trials at KKU farm in the dry season 2008 (26.7 t ha^{-1}) and the dry season 2006 (15.7 t ha^{-1}), whereas the trail at KKU farm in the rainy season 2008 had the lowest yield of only 9.8 t ha^{-1}. Therefore, the differences in environments created larger differences in tuber yield than did the differences in genotypes and G×E interactions. Growing Jerusalem artichoke in the dry season with irrigation generally yields better than growing in the rainy season.

JA 89, CN 52867 and JA 37 were the best yielding clones across all environments with yields of 18.9, 18.8 and 18.0 t ha^{-1}, respectively. They were also the top three cultivars in at least three environments. However, the HEL 53, HEL 69 and HEL 68 genotypes yielded at KKU farm in the dry season 2006 better than did the three top-yielding cultivars and the JA 102 genotypes also yielded better than did the three top-yielding cultivars at Chaiyaphum trial, showing specific adaptation to environments.

Tuber number: Jerusalem artichoke accessions were significantly different in Tuber number, ranging between 11 and 60 tubers with 24 tubers for overall mean (Table 5). The lowest tuber number (11) was observed in some cultivars grown in some environments and JA 89 was the only one genotype showing the highest tuber number (60) grown at KKU farm in the dry season 2007. Variation among cultivars for tuber number was also high, ranging from 18 tubers in KKU Ac 001 genotypes to 36 tubers in JA 37. Variation among environments for tuber number was also high, ranging from 14 tubers in the trail at KKU farm in the dry season 2008 to 32 tubers in the trial at KKU farm in the dry season 2007.

The trials at KKU Farm in the rainy season 2005 and dry season 2007 and the trial at Chaiyaphum in the dry season 2007 had the highest tuber number (30, 32 and 30 tubers, respectively). It is noted that high number of tubers could be found in both dry and rainy seasons although dry season favored higher tuber number than did in the rainy season. The cultivars with the best performance for tuber number were JA 37, CN 52867 and JA 89 with tuber numbers of 36, 35 and 34, respectively. It is also noted here that the highest ranks for fresh tuber weight and tuber number were very similar (JA 89, CN 52867 and JA 37, respectively). These cultivars showed the highest tuber numbers at least four environments and specific adaptation to specific environments.

Weight of individual tubers (Tuber size): Weights of individual tubers ranged from 29 g in the trial at KKU farm in the dry season 2006 to 262 g in KKU farm in the dry season 2008 with overall mean of 96 g. HEL 69 and JA 89 showed the lowest and the highest tuber weight,

Table 5: Tuber No. plant^{-1} of 15 Jerusalem artichoke clones grown at 9 environments during 2005-2008

	Environment									
Genotype	E1	E2	E3	E4	E5	E6	E7	E8	E9	Genotype mean
JA 37	54.0	36.0	25.0	40.0	28.0	52.0	51.0	21.0	19.0	36.0
JA 38	40.0	33.0	27.0	45.0	36.0	41.0	34.0	23.0	20.0	33.0
JA 67	23.0	22.0	26.0	26.0	28.0	11.0	35.0	16.0	12.0	22.0
JA 89	42.0	34.0	15.0	27.0	60.0	29.0	31.0	44.0	22.0	34.0
HEL 53	19.0	22.0	19.0	20.0	26.0	25.0	31.0	17.0	10.0	21.0
JA 102	20.0	18.0	13.0	16.0	31.0	22.0	23.0	11.0	14.0	19.0
HEL 335	22.0	20.0	16.0	13.0	35.0	22.0	27.0	11.0	13.0	20.0
HEL 231	25.0	20.0	21.0	17.0	26.0	25.0	24.0	14.0	12.0	20.0
HLE 69	32.0	25.0	15.0	21.0	41.0	31.0	26.0	17.0	17.0	25.0
HEL 61	19.0	21.0	17.0	19.0	31.0	27.0	26.0	15.0	12.0	21.0
HEL 65	26.0	19.0	12.0	11.0	26.0	26.0	21.0	17.0	11.0	19.0
HEL 68	31.0	24.0	21.0	26.0	35.0	25.0	30.0	12.0	12.0	24.0
HEL 66	25.0	20.0	26.0	18.0	28.0	20.0	23.0	12.0	11.0	20.0
CN 52867	53.0	35.0	23.0	33.0	35.0	56.0	41.0	20.0	20.0	35.0
KKU Ac 001	17.0	16.0	13.0	14.0	21.0	18.0	30.0	19.0	11.0	18.0
Environmental mean	30.0	24.0	19.0	23.0	32.0	29.0	30.0	18.0	14.0	24.0
LSD	6.9	2.1	3.3	5.9	5.6	7.7	7.4	3.8	2.5	5.0

Environment identification: E1: KKU farm rainy season 2005, E2: KKU farm dry season 2006, E3: KKU farm dry season 2006, E4: KKU farm rainy season 2007, E5: KKU farm dry season 2007, E6: Udon Thani dry season 2007, E7: Chaiyaphum dry season 2007, E8: KKU farm rainy season 2008, E9: KKU farm dry season 2008

Table 6: Weight of individual tubers (g) of 15 Jerusalem artichoke clones grown at 9 environments during 2005-2008

	Environment									
Genotype	E1	E2	E3	E4	E5	E6	E7	E8	E9	Genotype mean
JA 37	34.0	63.0	136.0	51.0	58.0	39.0	81.0	75.0	83.0	69.0
JA 38	37.0	62.0	102.0	51.0	50.0	39.0	105.0	55.0	57.0	62.0
JA 67	43.0	34.0	103.0	35.0	38.0	68.0	98.0	26.0	116.0	62.0
JA 89	48.0	68.0	202.0	72.0	40.0	38.0	126.0	50.0	107.0	84.0
HEL 53	59.0	47.0	237.0	73.0	84.0	73.0	84.0	108.0	262.0	114.0
JA 102	56.0	54.0	224.0	62.0	66.0	77.0	234.0	93.0	207.0	119.0
HEL 335	53.0	48.0	214.0	59.0	55.0	44.0	122.0	94.0	176.0	96.0
HEL 231	65.0	90.0	163.0	68.0	110.0	71.0	149.0	130.0	162.0	112.0
HLE 69	53.0	29.0	256.0	54.0	45.0	65.0	154.0	37.0	163.0	95.0
HEL 61	71.0	49.0	193.0	80.0	57.0	51.0	151.0	86.0	223.0	107.0
HEL 65	105.0	134.0	258.0	89.0	75.0	52.0	213.0	43.0	147.0	124.0
HEL 68	52.0	44.0	186.0	46.0	40.0	72.0	109.0	92.0	221.0	96.0
HEL 66	43.0	57.0	140.0	64.0	84.0	87.0	170.0	99.0	202.0	105.0
CN 52867	44.0	82.0	150.0	55.0	50.0	91.0	101.0	65.0	74.0	79.0
KKU Ac 001	55.0	34.0	266.0	98.0	102.0	92.0	132.0	115.0	163.0	117.0
Environmental mean	55.0	60.0	189.0	64.0	64.0	64.0	135.0	78.0	158.0	96.0
LSD	13.8	16.6	16.9	11.5	17.4	17.1	36.6	20.4	38.7	21.0

Environment identification: E1: KKU farm rainy season 2005, E2: KKU farm dry season 2006, E3: KKU farm dry season 2006, E4: KKU farm rainy season 2007, E5: KKU farm dry season 2007, E6: Udon Thani dry season 2007, E7: Chaiyaphum dry season 2007, E8: KKU farm rainy season 2008, E9: KKU farm dry season 2008

respectively (Table 6). Cultivar means across environments ranged from 62 g in JA 38 and JA 67 to 124 g in HEL 65. The three top performers were HEL 65, JA 102 and HEL 53 with tuber weights of 124, 119 and 114 g, respectively. The environmental means varied from 55 g at KKU farm in the rainy season 2005 to 189 g at KKU farm in the dry season 2006. The variation among environments contributed a large difference in tuber weight than did the variations among genotypes and genotype×environment interaction. However, the variation caused by G×E interaction was still greater than that caused by genotypes. Growing Jerusalem artichoke in the dry season tended to have larger tuber size than in the rainy season.

Correlation: Positive and significant correlation coefficient (0.21*) between tuber fresh weight and tuber number was observed, indicating that tuber number might play a significant contribution to tuber yield in some cultivars (Table 7). When correlation coefficients were calculated from each cultivar, the correlation coefficients between tuber yield and tuber number ranged between -0.12 and 0.55. The data were convincing that tuber yields of some cultivars were dependent on tuber number. However, the correlation coefficient (0.68**) between tuber fresh weight and weight of averaged one tuber were much stronger, showing higher dependence of tuber yield on size of individual tubers. The correlation coefficients of individual cultivars also supported the

Table 7: Correlation coefficients among tuber fresh weight, tuber No. plant^{-1} and weight of individual tuber (tuber size) of 15 Jerusalem artichoke clones grown at 9 environments during 2005-2008

Genotype	C_{12}	C_{13}	C_{23}
JA 37	0.302	0.533	-0.587
JA 38	0.254	0.803**	-0.351
JA 67	0.548	0.768**	-0.013
JA 89	-0.125	0.638	-0.714*
HEL 53	0.017	0.723*	-0.629
JA 102	0.261	0.789*	-0.257
HEL 335	0.255	0.744*	-0.359
HEL 231	0.325	0.722*	-0.379
HEL 69	-0.222	0.899*	-0.514
HEL 61	-0.024	0.795**	-0.545
HEL 65	0.138	0.833**	-0.396
HEL 68	-0.050	0.715*	-0.641
HEL 66	0.383	0.688*	-0.317
CN 52867	0.494	0.702*	-0.221
KKU Ac 001	0.516	0.657*	-0.209
Overall	0.206*	0.682**	-0.440**

C_{12}: Correlation from tuber fresh weight across tuber number plant^{-1}, C_{13}: Correlation from tuber fresh weight across weight of individual tuber (tuber size) and C_{23}: Correlation from tuber number plant^{-1} across weight of individual tuber (tuber size). *,**Significant at 0.05 and 0.01 probability levels, respectively

Table 8: Estimates of stability parameters for tuber fresh weight, tuber number plant^{-1} weight of individual tubers of 15 Jerusalem artichoke clones evaluated at 9 environments during 2005-2008

Genotype	Tuber fresh weight (b_i)	Tuber No. plant^{-1} (b_i)	Weight of individual tubers (b_i)
JA 37	0.83 (0.05)	1.63** (0.29)**	0.54 (0.03)
JA 38	0.52* (0.07)	0.98 (0.12)**	0.38** (0.04)
JA 67	0.47* (0.03)	0.61 (0.14)*	0.61 (0.04)
JA 89	0.78 (0.06)	1.18** (0.42)**	0.98 (0.05)
HEL 53	0.66* (0.08)**	0.80 (0.06)	1.36** (0.10)**
JA 102	0.96* (0.05)	0.85 (0.06)	1.47** (0.06)
HEL 335	0.99 (0.04)	1.07 (0.07)	1.21** (0.03)
HEL 231	1.11** (0.05)	0.73 (0.04)	0.71 (0.05)
HLE 69	0.92 (0.05)	1.23** (0.08)	1.49** (0.05)
HEL 61	0.90 (0.04)	0.86 (0.05)	1.23** (0.05)
HEL 65	0.97 (0.08)**	0.88 (0.07)	1.19 (0.10)**
HEL 68	0.86** (0.05)	1.18** (0.06)	1.21** (0.06)
HEL 66	1.24* (0.04)	0.71 (0.08)	0.92 (0.07)*
CN 52867	0.65* (0.09)**	1.72** (0.20)**	0.49 (0.05)
KKU Ac 001	0.55** (0.05)	0.56 (0.09)*	1.21** (0.07)*

b_i: Regression coefficient. *,**Significantly different from 1.0 at 0.05 and 0.01 level of probability, respectively. Number in parenthesis indicates standard deviation and *,** indicates significant difference from 0 at 0.05 and 0.01 probability levels, respectively

overall correlation coefficient. In contrast, the correlation coefficient between tuber number and weight of averaged one tuber was negative and highly significant (-0.44**). Correlation coefficients of individual cultivars also supported the overall coefficient. The results might indicate that, although these characters give contribution to yield, obtaining high tuber weight is on the expense of tuber number.

Tuber size showed high specific adaptation or high G×E interaction. HEL 53 and JA 102 won the top-three places for large tuber size at only two environments, whereas HEL 65 won in five environments. However, the cultivars with the largest tubers did not yield better than the cultivars with smaller tubers. In contrast, superior cultivars that won at many environments such as HEL 231, HEL 61, HEL 68 and KKU Ac 001, did not won the top-three places.

Stability parameter: Stability of any cultivar for any character was determined by its stability coefficient and the standard deviation associated with the stability coefficient. Stability coefficient itself can be interpreted in three different ways. The coefficient that is not different from 1 indicates that the cultivar respond to environmental change in the same magnitude. This means that, if environments change in yield of 1 unit, the cultivar should also change 1 unit and the cultivar is stable across environments. The coefficient that is lower than 1 indicates that the response of the clone to environmental change is rather low. In contrast, the coefficient that is higher than 1 indicates that the cultivar usually performs well under favorable environments than unfavorable environments.

Standard Deviation (SD) associated with stability coefficient indicates degree of performance fluctuation across environments. If the standard deviation is larger than 0, the performance of the clone is said to be highly fluctuated.

In addition to stability parameters, yield and other economically important characters are also important in determining superior genotypes.

Seven cultivars (JA 37, JA 89, HEL 335, HLE 69, HEL 61, HEL 65 and HEL 68) were more consistent for fresh tuber yield as their stability parameters were not significantly different from 1 (Table 8). These cultivars showed yield increase with favorable environments. Two of these cultivars (JA 37 and JA 89) were promising for possible release because of their wide adaptation and high tuber fresh yield. However, HEL 66 was promising for adaptation to favorable environments, whereas CN 52867 and KKU Ac 001 showed good adaptation to unfavorable environments. CN 52867 also had high fresh tuber yield.

Three cultivars (HEL 53, HEL 65 and CN 52867) were more fluctuated for tuber yield as indicated by their significant standard deviations. Based on tuber yield and stability parameter for tuber yield, JA 37 and 89 are more promising for release for growing in a wide range of environments because of their high and stable yield. The CN 52867 was less stable but had high yield under unfavorable environments.

Ten of 15 cultivars were more stable for tuber number (Table 8). These included JA 38, JA 67, HEL 53, JA 102, HEL 335, HEL 231, HEL 61, HEL 65, HEL 66 and KKU Ac 001. However, tuber numbers of JA 38, JA 67 and KKU Ac 001 were more fluctuated.

There were five clones showing high tuber number under favorable environments. They were JA 37, JA 89, HEL 69, HEL 68 and CN 52867, but JA 37, JA 89 and CN 52867 were more fluctuated for tuber number.

If high tuber number is to be selected, JA 37, JA 89 and CN 52867 are the most promising cultivars. Unfortunately, they did not show stability for tuber number. The cultivars with stable tuber yield generally had low tuber number.

JA 38 had the lowest stability coefficient for tuber size, indicating that it was not sensitive to environmental change (Table 8). There were seven cultivars having stability coefficients that were not different from 1. They were JA 37, JA 67, JA 89, HEL 231, HEL 65, HEL 66 and CN 52867, but HEL 65 was more fluctuated because the standard deviation associated with the stability coefficient was higher than 0. Other seven cultivars (HEL 53, JA 102, HEL 335, HEL 69, HEL 61, HEL 68 and KKU Ac 001) showed better adaptation to more favorable environments as indicated by their high stability coefficients. Among these cultivars, HEL 53 and KKU Ac 001 were more fluctuated as the standard deviations associated with stability coefficients were higher than 0.

If large tuber size is to be selected, JA 102, HEL 65 and KKU Ac 001 should be the best candidates. HEL 65 had wide adaptation but it was rather fluctuated for tuber size, whereas JA 102 and KKU Ac 001 had specific adaptation to better environments. JA 102 was better than KKU Ac 001 because its performance for tuber size was more consistent than that of KKU Ac 001.

DISCUSSION

Jerusalem artichoke is underutilized crop and the study on agronomy is still insufficient. Optimum agronomic practices are still unknown for this crop especially under growing conditions in the semi arid tropics. There have been several reports on yield performance of Jerusalem artichoke. However, direct comparison of yield performance is not possible because growing conditions and agronomic practices varied considerably.

Yield is always interesting for any crop. Fresh tuber yields of Jerusalem artichoke varied between 3.0 and 38.9 t ha^{-1} and environmental effect was the major cause of variation in tuber yield. However, the tuber yields obtained in this study were in a range of those earlier reported. At a plant density of 40,000 plants ha^{-1} Andersen (1992) obtained average yields of 12.7 to 61.8 t ha^{-1}, depending on varieties. Baldini *et al*. (2006) reported that tuber yield of Jerusalem artichoke grown in Italy varied between 55.5 and 80.0 t ha^{-1}, depending on locations. Rodrigues *et al*. (2007) obtained maximum tuber fresh weight of 65.6 t ha^{-1} during the growing seasons of 2004-2006 field trials in NE Portugal. Losavio ***et al.*** (1997) reported average tuber yields ranging between 34.9 and 43.8 t ha^{-1} depending on cultivars, irrigations and years.

Yield trials in the United States indicated that higher fresh tuber yields were obtained under temperate and semi tropical biospheres, whereas yields under tropical climate in the Southern United States were very low (Yungen, 1992). In this study, the highest yield (30.3 t ha^{-1}) was obtained at the trial in Chaiyaphum province where max/min temperature was lowest (29.3/19.7°C) and alleviation is highest (800 m.a.s.l). Therefore, growing Jerusalem artichoke in the semi arid tropics can be more productive in the areas with high alleviation.

Jerusalem artichoke can be grown successfully in a wide range of environmental conditions. Under optimum conditions, Jerusalem artichoke can be as high as three meters and can produce considerable biomass (Parameswaran, 1999). These properties are interesting for use as energy crop (Szambelan *et al*., 2004). Under growing conditions in Thailand, Jerusalem artichoke has never been taller than two meters and it is much shorter when grown in the dry season under shorter photoperiods. Therefore, growing under different conditions requires different agronomic practices and optimum population densities to obtain optimum yield.

In addition to the difference in physical conditions, biological conditions can also cause high variation in yield. In the rainy season where the weather is hot and humid, the crop can be vulnerable to tuber rot caused by several fungal diseases.

Although Jerusalem artichoke has been reported as hardy plant, it is not resistant to drought. Drought can cause severe loss and irrigation is still necessary for commercial production even under rainfed conditions. In the environments where rainfall was very low such as E3 (280.5 mm) and E9 (170.3 mm), irrigation could sustain fresh tuber yield. The environments that are detrimental to fresh tuber yield are those with high rain and high temperature especially high rain at harvest.

However, Jerusalem artichoke better competes with weeds and one manual weed control at early growth is sufficient for normal growth and optimum yield. Planting at 40,000 plants ha^{-1} is somewhat suboptimum as the crop did not showed severe lodging. Planting at higher plant density might increases tuber yield but the crop can be vulnerable to tuber rot and the plant density in the tropics can be as high as double of those planted in the temperate regions.

Jerusalem artichoke tubers have chain growth habit (Rodrigues *et al*., 2007) especially when soil moisture is excessive for optimum growth. These conditions can cause high tuber number but low yield because the tubers are highly-branched and very small. Comparison of tuber number among different studies is difficult because the authors use different criteria. In this study, tuber numbers ranged between 11 and 60 tubers per plant and the tubers that attached to the crowns were considered as tubers irrespective of their branches. Losavio *et al*. (1997) observed tubers per plants ranging between 21.5 and 30.8 tubers depending on cultivars, irrigations and years in the evaluation of three cultivars. McLaurin *et al*. (1999) found that tuber number (85.5 tubers plant^{-1}) of Jerusalem artichoke reached a maximum 24-28 weeks after planting.

It is still not clear whether growing in the dry and rainy season could yield more tuber number, but it seemed likely that excessive soil moisture promotes chain growth and branching of tubers. Differences in environments, cultivars and interaction of these factors similarly contributed to variation in tuber number.

Large tubers are important for commercial production. In this study, averaged weight of individual tubers ranged between 29 and 262 g. Tuber size was rather sensitive to environmental change and G x E interaction was also high, whereas difference among cultivars was rather low. Similarly, Losavio *et al*. (1997) observed average tuber weights ranging between 26.5 and 40.4 g depending on cultivars, irrigations and years.

Tuber size is an important character for the cultivars to be released for commercial production as it facilitates mechanized harvest and the price is higher than smaller tubers. Therefore, larger tubers could compensate lower yield.

Correlation coefficients indicated that larger tubers contributed to higher tuber yield in some cultivars and it is possible to select cultivars with high tuber yield and large tubers. High number of tubers is generally associated with higher tuber yield and the relationship was much stronger than that of tuber yield and tuber size, but the relationship between tuber size and tuber number was reverse.

The G×E interactions, thought significant, were much lower than environmental main effects and cultivar main effects for fresh tuber yield, tuber number and tuber size. Therefore, environments suitable for growing Jerusalem artichoke and cultivars showing adaptation to a wide range of environments could be readily identified. Growing in the highland areas with low temperature was best suited for commercial production and growing under excessive rain conditions should be avoided.

Differential responses of Jerusalem artichoke cultivars to environments were observed for fresh tuber yield, tuber number and tuber size. This is not unexpected because the cultivars have diverse origins. The response patterns based on stability parameter could be classified into three distinct groups namely the cultivars with stability parameters that equal to 1, the cultivars with stability parameters higher than 1 and the cultivars with stability lower than 1.

The responses for fresh tuber yield felled into all groups, indicating that selection of superior genotypes could be carried out for three different purposes; general adaptation, specific adaptation to favorable environments and specific adaptation to unfavorable environments.

The responses for tuber number felled into two distinct groups e.g., the genotypes with general adaptation and the genotypes with specific adaptation to favorable environments. This indicated that genotypes had tendency to produce more tubers under favorable conditions.

The responses for tuber size felled into three categories but there was only one genotype in the group with stability parameter lower than 1. This also indicated, with some exception, the tendency to yield large tuber size under favorable environments.

The genotypes that perform more reliable across environments for fresh tuber yield, tuber number and tuber are required for possible release. High standard deviations indicated high fluctuations for these characters. When all characters were compared, fresh tuber yield was most reliable across environments. In addition to these characters, the tubers must be of smooth skin and good color.

Based on fresh tuber yield and stability parameter, the cultivar JA 89 was most promising for growing under a wide range of environments, whereas the cultivar HEL 65 was the best performer for tuber size.

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