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Radicchio (*Cichorium intybus* l.) variety selection for the Chilean central area

Ricardo Pertuzé*, Rodrigo Bravo, Paola Silva

Departamento de Producción Agrícola, Facultad de Ciencias Agronómicas, Universidad de Chile, Casilla 1004, Santiago, Chile

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ABSTRACT

In the Chilean market there are hybrid varieties of radicchio (*Cichorium intybus* L.) with high yield and homogeneity, where its main limitation is the high cost of the seed. The most important variety is 'Leonardo', which represents 90% of the market. Moreover, it is believed that there are open-pollinated varieties that could be used as an alternative to hybrids at lower cost. The study aim was to select open-pollinated varieties with equal or better exportable yield than 'Leonardo', in order to establish bases on the recommendation of cultivars for the Chilean central area. Eleven varieties of radicchio were evaluated in a randomized complete block design with five replications. The trial was conducted in four locations of Chilean central area, during seasons 2007–2008. At each site, three planting dates were evaluated. The combination of locality × transplant date generated 12 environments. Exportable yield, head weight, percentage of sick plants, early flowering bolting and exportable color were evaluated. Combined analyzes of variance, stability, additive main effects and multiplicative interaction model (AMMI), sites regression analysis (SREG) and principal components were made. The exportable yield of the varieties ranged from 23.34 t ha^{-1} ('Leonardo') to 6.84 t ha^{-1} ('CH121'), and the environments ranged between 25.89 and 8.18 t ha^{-1}. The analysis of the exportable yield variance showed significant G × E effect. The type of radicchio (Treviso or Chioggia) was the main cause of interaction for exportable yield. In terms of exportable yield, 'Ciro' (Chioggia) could be considered as a good alternative to 'Leonardo' in the mega environment formed by the three planting dates of Polpaico, Santo Domingo and Lampa, while 'Tullio' (Treviso) could be an alternative in the three planting dates of Padre Hurtado. 'Ciro' yield 18.7% less than 'Leonardo' ($P < 0.05$) but showed better stability than 'Leonardo'; and 'Tullio' yield 24% more than 'Leonardo' in the three planting dates of Padre Hurtado ($P < 0.05$). Exportable yield reduction is mainly due to diseases.

1. Introduction

Radicchio (*Cichorium intybus* L.) is a biennial vegetable crop from the Asteraceae family, which originated in the orient and has been traditionally cultivated in Italy because of its leaf head (Mencarelli, 2014). Nowadays it is appreciated in international markets especially for its color and bitterness, but also for its nutritional quality and pharmaceutical potential (Harsh and Ravishankar, 2001; Wang and Cui, 2011), being used mainly for fresh consumption.

According to leaf color radicchios can be classified into two groups, red and variegated. The red ones have red blade and white central vein, and according to their head shape three types can be found, "Rosso di Treviso" (oblong), "Rosso di Verona" (heart shape) and "Rosso di Chioggia" (round). The variegated have yellow-greenish blade with green, red and whitish spots or lines, and can be found the "Variegato di Castelfranco" and the "Variegato di Chioggia" types (Raulier et al., 2015).

Radicchio is an alogamus plant with high outbreed percentage (Kiers et al., 1999). Its high heterocis is correlated with a big genetic variability that is responsible for the difficulty to select varieties (Varotto et al., 1995). Additionally this species has self-incompatibility and high endogamic depression limiting the production of homozygous and also limiting breeding (Eenink, 1981). In Italy many growers traditionally select their own populations for next year crop simply according to the morphological characteristics of their interest (Barcaccia et al., 2003). For that reason most of the populations are heterogeneous and with different climatic requirements and in most cases low yields (Gianquinto, 1997). Never the less, due to male sterility, some hybrid varieties have been developed, which carry high homogeneity and high

* Corresponding author.
E-mail addresses: rpertuze@uchile.cl (R. Pertuzé), rodrigo.bravo@pioneer.com (R. Bravo), psilva@uchile.cl (P. Silva).

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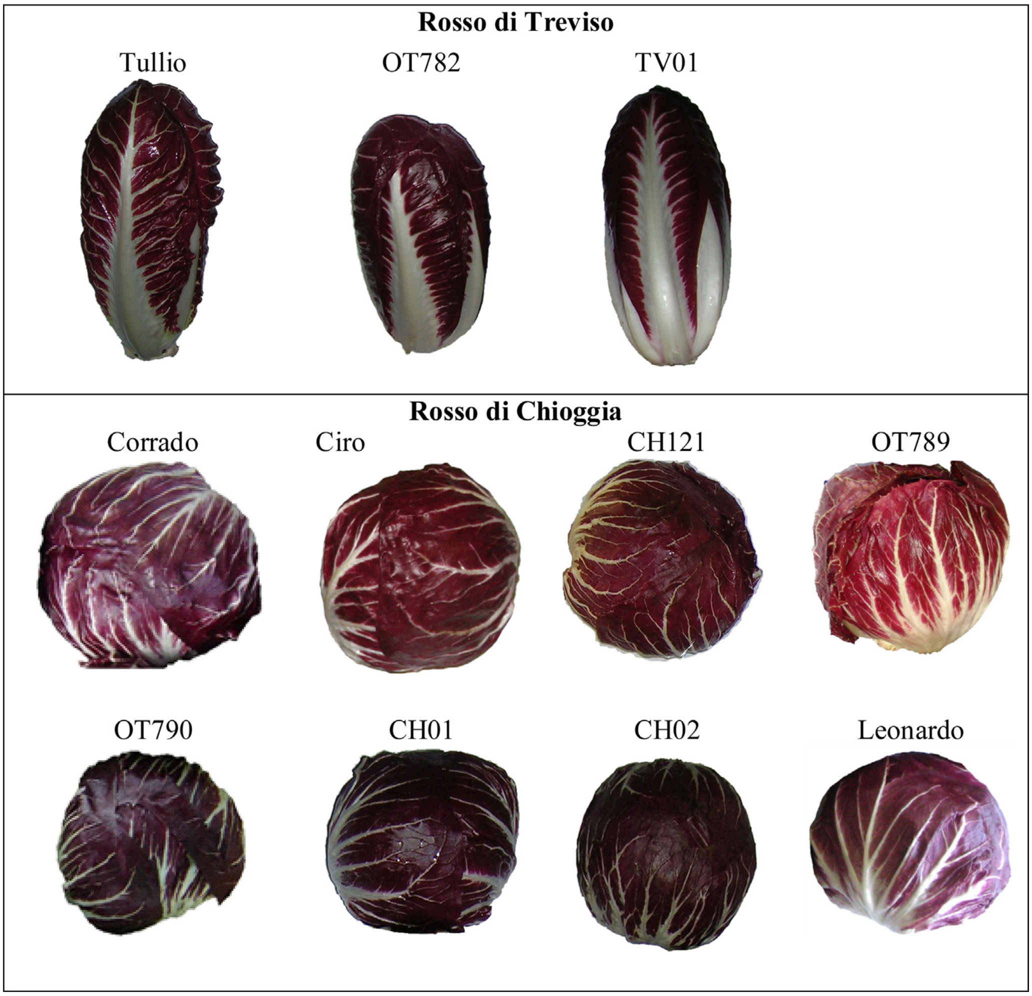

Fig. 1. Commercial heads of the evaluated varieties.

yield, but the seeds are considerably more expensive than the standard ones.

This specie was introduced to Chile in the mid 80s as a fresh product with high export potential. It has been cultivated from the region of Coquimbo to the Maule region, concentrating most of the production in the Metropolitan and Valparaiso regions. The production has been exported mainly to USA and Europe.

The radicchio exportable yield can be measured as the total weight of the commercial heads (Hill, 1988). The quality index center in compact heads, with the colors and shape characteristic of the type, specially white veins without necrosis or rotting in the leaves (Mencarelli, 2014). This quality and yield can be influenced by a number of factors, such as weather conditions, soil water content, fertilization, planting date, harvest date, type and variety of radicchio (Berlien, 2004; Žnidarčič et al., 2004; Monti et al., 2005; Biesiada and Kolota, 2008; Francke and Majkowska-Gadomska, 2008; Devacht et al., 2009; Lucarini et al., 2012).

Different varieties have differentiated adaptation according to agroclimatological characteristics having specific adaptation to specific locations. Chile radicchio production areas have diverse conditions and no varieties studies have been run for variety selection or genotype × environment interaction. In the same way there are no cultural management recommendations to obtain the yield potential in each area. Several authors reported low exportable yields due to the heterogeneity of different varieties (Carrasco et al., 1998; Lazzarin et al., 2000; Rangarajan and Ingall, 2001; Berlien, 2004).

Table 1
Tested radicchio varieties.

Name	Type	Reference	Characteristic
'Tullio'	Treviso	Incao	Early, OP
'OT782'	Treviso	Salmáso	Early, OP
'TV01'	Treviso	Sotomarina	Early, OP
'Corrado'	Chioggia	Incao	Medium late, OP
'Ciro'	Chioggia	Incao	Early, OP
'CH121'	Chioggia	Sais	Early, OP
'OT789'	Chioggia	Salmáso	Early, OP
'OT790'	Chioggia	Salmáso	Late, OP
'CH01'	Chioggia	Sotomarina	Early, OP
'CH02'	Chioggia	Sotomarina	Early, OP
'Leonardo'	Chioggia	Bejo Zaden	Early, hybrid

OP: open pollinated variety.

The most common variety in Chile is 'Leonardo'. Even though this variety is an expensive hybrid, became to be 90% of the Chilean crop in 2009. There are other open pollinated varieties available in Chile of considerable lower cost as alternatives, but there is no information of their characteristics of yield stability or specific adaptation.

The lack of information suggest a study of the adaptation patterns of hybrid and open pollinated varieties in the Chilean central area, in order to detect the ones that better perform in local areas, as well as separate production subareas or mega-environments for which specific variety selection strategies can be define to treat the present genotype × environment interactions (G × E). The use

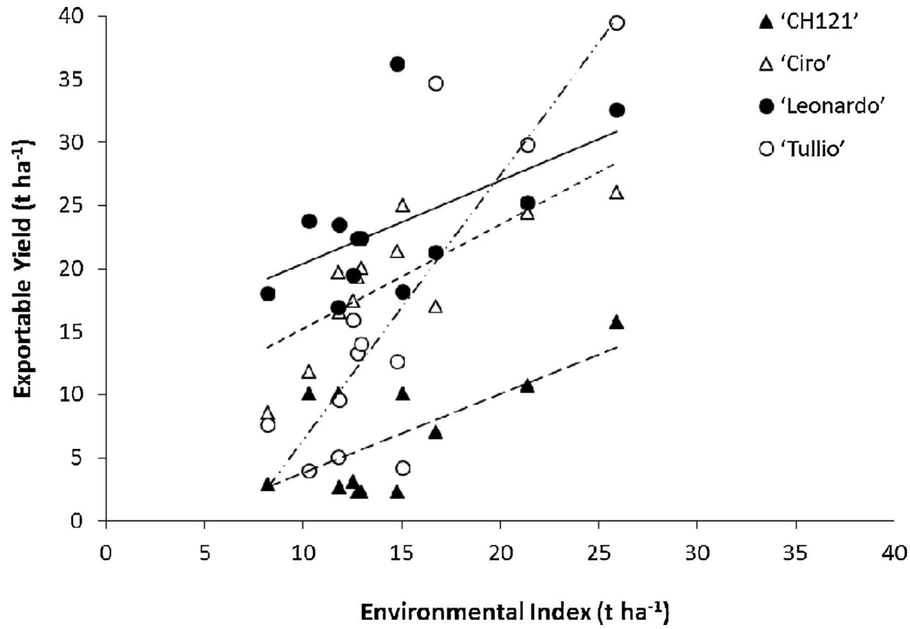

Fig. 2. Stability analysis of exportable yield of 'Leonardo', 'Tullio', 'CH121' and 'Ciro' radicchio varieties in 12 environments.

of historic information allow the analysis of a big sample of genotypes and environments and allow to accommodate the effects of the G × E interactions (DeLacy et al., 1996), although require of complex statistic tools that allow ordering the unbalance from the fact of the use of different genotypes in different environments or years (Kempton and Lockwood, 1984; DeLacy et al., 1996; Smith et al., 2001).

The G × E interaction difficult the variety selection because of the inconsistence of the genotypes in different environments. Breeding programs consider trials in different environments to quantify the effect of the interaction in the final variety selection. This type of yield trials involves multiple environments and genotypes (Paderewski et al., 2011). From the G × E interaction the specific adaptation, the stability and mega environments can be observed (Yan and Hunt, 2001). For the interaction study and the analysis derived from it, interaction of multiplicative model analysis (AMMI) (Paderewski et al., 2011) have been widely used among breeders. The GGE biplots (Yan and Hunt, 2001) are methodologies for identification of mega environments, variety selection among each environment and selection of environments for these trials. This type of plots can be obtained from models that incorporate external variables (covariables), from the genotypes as well as from the environments (Vargas et al., 2001).

The goals of this work is evaluate the G × E interaction for exportable yield and its relation with yield components in radicchio and identify open-pollinated varieties with wide and specific adaptation, among and between locations with equal or better exportable yield than 'Leonardo'.

2. Materials and methods

2.1. Genotypes and environments

Chioggia and Treviso radicchio varieties types were evaluated, 10 open pollinated varieties and 1 hybrid ('Leonardo') (Table 1 and Fig. 1). Both types have bright red leaf-blades and white vein. They differ in the head shape, Chioggia is rounded and Treviso elongated (Gianquinto and Pimpini, 1989).

The genotypes were evaluated in four locations in Chilean central area (Table 2). At each site three planting dates were evaluated (Date 1: November 12, Date 2: November 27 and Date 3: December 12), thus the location × planting date combination generated a total of 12 environments. In each environment the genotypes were in a completely randomized block design was established with five replicates. An experimental unit of three ridges 3.5 m long and spaced 0.75 m between rows was used (7.875 m^2). As the sampling unit, 10 radicchios of the central ridges were used.

2.2. Agronomic management of the experiment

Plants were produced in nurseries to ensure initial quality of the material and achieve homogeneous plants when transplanting. Seedlings were transplanted manually with 4–5 leaves, which occurred about 38 days after planting. An equivalent of 79,000 plants ha^{-1} were established. Irrigation and fertilization vary depending on the locations. In Lampa 200 kg Horticals Mix (17-21-18) were used and 200 kg of granulated urea (46-0-0) in several dose. For other locations fertilization was 100–120 kg ha^{-1} of N applied in 3 partitions, 150–200 kg ha^{-1} of P_2O_5 and 100–150 kg ha^{-1} of K_2O at sowing. Manual weedings and cultivator every 20 days were performed from the date of transplant. Imidacloprid (20 mL 100 L^{-1} water) and thiamethoxam (200 g ha^{-1}) were applied as pest control. The first application was made 30 days after planting to control aphids, prawns and thrips mainly and the subsequent application was made 15–20 days before harvest.

2.3. Measurements

Leaf number at head closing (LN). Leaves were counted in each of 10 plants of the central furrow when the head of the plants began to close.

Sick plant percentage (SP%). Number of plants that presented some degree of rotting that limit growth, harvest or commercialization over the total number of plants established in the central furrow of each experimental unit.

Offtype percentage (Off%). Number of plants that differ morphologically form the expected type for the variety, over the total number of plants established in the central furrow of each experimental unit.

Table 2
Description of evaluated locations in Chilean central area.

Location	Latitude	Longitude	Altitude (m.s.n.m)	Avg. temp (°C)	RH (%)	Soil textural class
Polpaico	33°07'12"S	70°52'00"O	544	23.7	52.3	loam
Lampa	33°16'08"S	70°52'52"O	499	22.9	50.1	Fine sandy loam
Padre Hurtado	33°34'00"S	70°53'00"O	392	19.6	70.2	Sandy loam
Santo Domingo	33°54'48"S	71°50'6"O	10	15.2	75.5	Sand clay loam

Table 3
Evaluated variables averages for the 11 varieties of radicchio.

Variety	Exportable yield ($t\,ha^{-1}$)	Yield ($t\,ha^{-1}$)	Sick plants (%)	Plants with premature bolting (%)	Off-type plants (%)	Harvested plants (%)	Head fresh weight (g)	Exportable color (%)	Leaf at head closing (number)
'Tullio'	18.7 b	21.8 b	39 b	1.6 b	0 b	59.0 c	440 a	82 c	14.6 b
'OT782'	13.6 d	17.9 d	39 b	3.9 b	0.3 b	57.2 c	313 d	91 a	14.1 c
'TV01'	12.6 d	14.5 d	42 b	3.0 b	0.7 b	54.7 c	332 c	87 b	15.9 a
'Corrado'	11.2 e	14.3 d	42 b	4.3 b	0.9 b	52.8 c	332 c	79 c	13.3 d
'Ciro'	19.0 b	24.3 a	17 d	2.5 b	0.5 b	79.8 a	384 b	78 c	9.8 k
'CH121'	6.8 f	10.2 e	47 a	8.3 c	1.8 a	43.0 d	295 d	61 d	11.4 g
'OT789'	16.6 c	19.6 c	21 d	4.1 b	0.3 b	74.1 b	337 c	84 b	10.9 i
'OT790'	10.3 e	17.7 c	43 b	6.2 c	1.0 b	50.3 c	446 a	54 e	12.1 e
'CH01'	16.5 c	20.1 c	26 c	3.2 b	0.5 b	70.1 b	365 b	81 c	11.3 h
'CH02'	15.7 c	19.1 c	22 d	6.3 c	0.7 b	70.6 b	348 c	81 c	11.8 f
'Leonardo'	23.3 a	25.3 a	16 d	0.4 a	0.8 b	82.8 a	386 b	92 a	10.2 j
Mean	14.9	18.3	32.0	4.0	0.7	62.5	362	79	12.3
Mean Treviso	15.0	18.1	40.0	2.8	0.3	57.0	362	87	14.9
Mean Chioggia	14.9	18.8	29.3	4.4	0.8	65.0	362	76	11.4

Different letters vertically indicate that significant differences exist for DGC multiple comparison test ($P < 0.05$).

Table 4
Evaluated variable averages for the 12 environments of 11 varieties of radicchio.

Environments	Exportable yield ($t\,ha^{-1}$)	Yield ($t\,ha^{-1}$)	Sick plants (%)	Plants with premature bolting (%)	Off-type plants (%)	Harvested plants (%)	Head fresh weight (g)	Exportable color (%)	Leaf at head closing (number)
Polpaico_1	12.8 d	16.6 d	40 b	0.1 d	0.1 b	59.6 c	348 c	75 c	17.8 a
Polpaico_2	14.0 d	17.7 d	42 b	0.2 d	0.2 b	57.3 c	397 b	79 c	15.9 b
Polpaico_3	17.6 c	19.8 c	40 b	0.2 d	0.1 b	59.8 c	398 b	89 b	12.6 e
Lampa_1	10.6 d	15.3 d	37 b	6.7 b	1.5 a	54.4 c	357 c	69 d	14.8 d
Lampa_2	16.1 c	19.7 c	31 c	2.1 c	0.6 b	66.5 b	370 c	82 b	12.0 g
Lampa_3	13.5 d	16.5 d	49 a	2.1 c	0.5 b	48.3 d	436 a	81 c	9.8 i
Padre Hurtado_1	16.7 c	21.7 c	15 e	14.4 a	0.6 b	69.6 b	402 b	74 c	10.6 h
Padre Hurtado_2	21.4 b	25.9 b	21 d	9.0 b	0.6 b	68.8 b	448 a	83 b	9.6 k
Padre Hurtado_3	25.9 a	28.3 a	16 e	4.2 c	0.4 b	79.3 a	449 a	92 a	7.4 l
Santo Domingo_1	8.2 e	10.2 e	36 b	1.8 c	1.3 a	60.7 c	215 e	76 c	15.0 c
Santo Domingo_2	12.5 d	15.7 d	25 d	2.0 c	1.3 a	71.5 b	278 d	79 c	12.4 f
Santo Domingo_3	11.8 d	15.1 d	37 b	0.8 d	0.8 b	61.3 c	303 d	77 c	9.7 j
Mean	15.1	18.5	33	4.0	0.63	62.3	367	80	12.3

Different letters vertically indicate that significant differences exist for DGC multiple comparison test ($P < 0.05$).

Premature bolting percentage (PB%). Number of bolting plants over the total number of plants established in the central furrow of each experimental unit.

Harvested plants percentage (HP%). Number of harvested plants over the total number of plants established in the central furrow of each experimental unit. Only fully developed compact heads were counted, and offtypes and bolting plants were discarded.

Head fresh weight (HFW). Each harvested plant of the experimental unit was weighted and recorded in grams.

Yield. It was estimated from the head fresh weight and the harvested plants percentage, considering an initial population of 79,000 plants ha^{-1} according to the following formula:

$$\text{Yield}\ (t\,ha^{-1}) = \frac{79,000 \times \text{Head fresh weight (g)} \times \text{Harvested plants (\%)}}{1,000,000}$$

Exportable color percentage ($E \times C\%$). Number of plants with exportable head color over the total number of harvested plants from each experimental unit. The following head color categories were considered: (1) green, variegated or red with green veins, (2) not very uniform pink dyes, (3) uniform red color and (4) dark red, purplish-red to purple. Only categories 3 y 4 were considered exportable.

Exportable yield (Ex yield). This value was obtained according to the following formula:

$$\text{Exportable yield}\ (t\,ha^{-1}) = \frac{\text{Yeild}\ (t\,ha^{-1}) \times \text{Exportable color (\%)}}{100}$$

weather variables. Maximum and minimum temperature and relative humidity were obtained daily throughout the growing season with a data logger (Keytag brand, model KTL-508) installed in each trial.

2.4. Statistical analyzes

Combined analysis of variance (ANOVA): the analyses were made for each of the evaluated variables. The analyses were adjusted for a factorial model with nested repeats in environments, considering the factors variety, environment and their interaction. A data set that includes 11 varieties evaluated in 12 environments were considered. Multiple comparisons test DGC 5% ($\alpha = 0.05$) was used for the comparison of means. The DGC is a particionante test method (no overlap of letters between means) recommended to compare five or more means (Di Rienzo et al., 2001).

The percentage variables were transformed by the following expression:

$$\mathrm{ARCSIN}\sqrt{\frac{x}{100}}$$

where x is the value to be converted. Thus the variables can be treated as parametric. All variables were tested for homogeneity of variance and normality of the data, prior to the application of ANOVA.

Stability analysis of genotypes: Linear regression analysis between the individual performance of each genotype and the average yield of all genotypes in each environment (environmental index), where the slope of the line obtained was the stability of the genotypes along the analyzed environments, the best cultivar was determined as the one that had a the greatest average yield (cultivar average in all environments) and the highest stability (Eberhart and Russell, 1966).

Additive main effects and multiplicative interaction model (AMMI)**:** The equation for this linear–bilinear model for the response of a genotype in a given environment can be expressed as follows (Crossa and Cornellius, 1997):

$$y = \mu + G_i + A_j + \sum_{n=1}^{r} \lambda_n \xi_{ni} \eta_{nj} + \rho_{ij} + \varepsilon_{ij}$$

where G is the efect of genotype i, $A_j$is the efect of environment j, $\sum_{n=1}^{r} \lambda_n \xi_{ni} \eta_{nj}$is the sum of multiplicative terms that model G × E interaction, composed by the interaction of the j-th environment, denoted as η_{nj}, of the i-th genotype for the same component or axis, denoted as ξ_{ni} and the eigenvalue (measure of variation associated with y axis denoted as λ_n). The parameter ρ_{ij}represents the portion of the ij-th term of the G × E interaction not explained by the multiplicative model and $\varepsilon_{ij}$is the random error term. The term ξ_{ni} can be interpreted as genotypic sensitivity to latent environmental factors, which are represented by η_{nj}in the j-th environment.

Sites regression model (SREG): The model to build a GGE biplot with the first two principal components (Yan and Hunt, 2001) is:

$$y_{ij} - \bar{y}_j = \lambda_1 \xi_{i1} \eta_{j1} + \lambda_2 \xi_{i2} \eta_{j2} + \varepsilon_{ij}$$

where y_{ij} is the mean yield of genotype i in environment j, $\bar{y}_j$is the mean of the genotypes in environment j, $\lambda_1$and$\lambda_2$are the eigenvalues for PC1 and PC2, respectively, $\xi_{i1}$and $\xi_{i2}$are the values of genotype i in PC1 and PC2 respectively, $\eta_{j1}$and η_{j2} are the values of environment j in PC1 and PC2 respectively and $\varepsilon_{ij}$is the residual term associated to the average observation of genotype i in environment j focused on the effects of environment j. The model is standardized to ensure that PC1 and PC2 have the same units.

Principal component analysis (PCA): In order to explain the variability of the genotype and the environments in relation to all the variables under study, a principal component analysis was done, which was to build unobservable variables (components) from observable variables (variables to be analyzed). The new variables (principal components) were obtained as linear combinations of the original variables and were represented on a biplot (Balzarini et al., 2005). Two PCA were conducted: the first analysis considering the 11 varieties of radicchio and 9 variables (harvested plants percentage, yield, exportable yield, sick plant percentage, premature bolting percentage, offtype percentage, leaf number at head closing, head fresh weight and exportable color percentage) and the second analysis considering the 12 environments and nine variables considered in the previous analysis.

InfoGen software version 2011 was used for statistical analyzes (Balzarini and Di Rienzo, 2011).

Table 5
Slope, intercept and R^2 values from the stability analysis of the 11 radicchio varieties under study.

Type	Variety	Slope (b)	Intercept (a)	R^2
Treviso				
	'Tullio'	1.95	−1.24	82.1
	'OT782′	1.18	−7.10	52.1
	'TV01′	1.25	−7.97	78.4
Chioggia				
	'Corrado'	0.80	−2.25	56.2
	'Ciro'	0.82	6.20	65.4
	'CH121′	0.75	−5.56	76.0
	'OT789′	0.71	4.19	26.3
	'OT790′	0.90	−4.69	57.8
	'CH01′	0.94	1.74	59.7
	'CH02′	0.83	0.04	28.4
	'Leonardo'	0.65	13.14	33.1
Mean		0.98	−0.32	56.0
Mean Treviso		1.46	−9.18	70.9
Mean Chioggia		0.80	1.60	50.4

3. Results

3.1. Exportable yield

The exportable yield of the 11 varieties showed a large degree of variation ranging from 6.84 t ha^{-1} ('CH121') to 23.34 t ha^{-1} ('Leonardo') (Table 3).

A wide degree of variation was also observed between environments ranging between 8.18 t ha^{-1} and 25.89 t ha^{-1}, the largest exportable yields were achieved in Padre Hurtado, regardless of planting date, and lower yields were reached in Lampa and Santo Domingo, in the first planting date (Table 4).

Exportable yield showed a highly significant effect for the G × E interaction ($P < 0.001$). Furthermore, 28.3% of the total sum of squares was due to interaction.

Parameter values obtained from individual regression of all varieties for exportable yield, on the average of the varieties in each environment are shown in Table 5. In general, it was observed that Treviso type varieties achieve high yields in high-performance environments and very low in environments with low environmental index, the values of slope regression are larger than 1, so it is concluded that they have specific adaptation to high yield conditions and they are very unstable. However, Chioggia type varieties such as 'Leonardo' and 'Ciro' have high average yield (Table 3) and low slope regression, so its behavior is fairly stable, adapting widely to all environments (Fig. 2).

However, the stability analysis limiting factor were low determination coefficient values (R^2) in some genotypes ('OT789', 'CH02', 'Leonardo'), which would account for the regression explaining less than 50% of the variation observed in these genotypes.

In the AMMI analysis for the exportable yield (Fig. 3) the first two principal components explain 70.4% of the variability, enough to explain the patterns due to the G × E interaction (Balzarini et al., 2005).

PC1 indicates that the most important aspect of the G × E interaction is explained by the type of radicchio. All Treviso type varieties ('Tullio', 'OT782', 'TV01') have positive values in the PC1. While the Chioggia type varieties have negative values. Treviso type

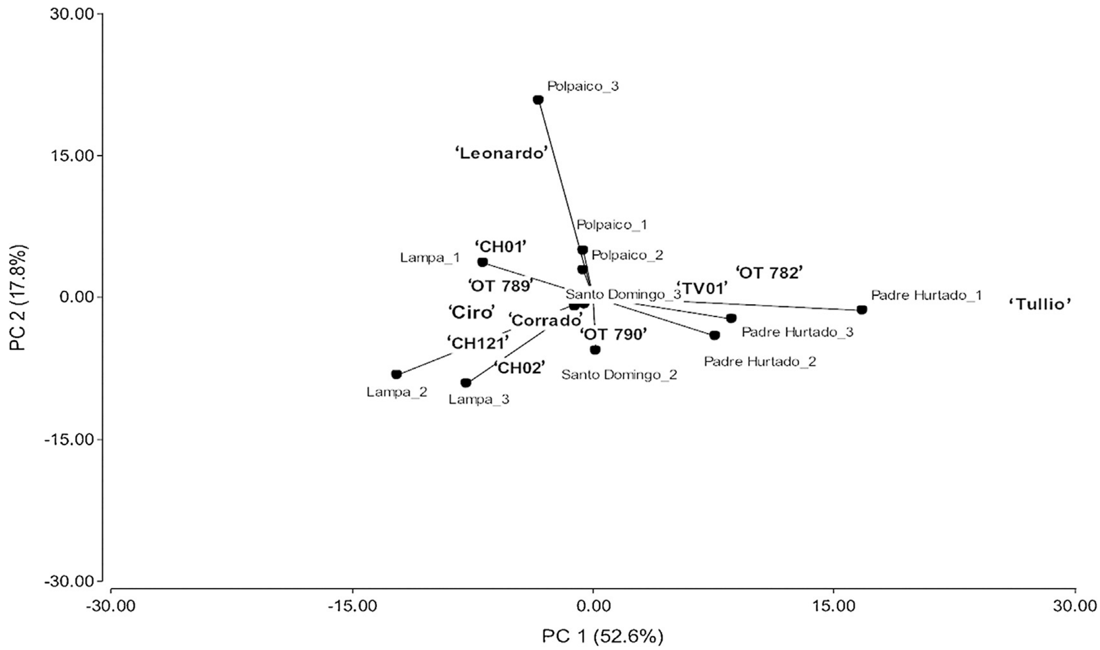

Fig. 3. Biplot from main additive effects and multiplicative interaction model (AMMI) made for the exportable yield of the 11 varieties of radicchio in 12 environments.

varieties have positive interaction with Padre Hurtado environments.

On the one hand, Padre Hurtado _1 and Lampa_2 environments are in the extreme of the range of variation of PC1 and therefore it is possible to conclude that they provide most of the contribution to explain G × E interaction patterns. On the other hand, Polpaico_3 is in the extreme of the range of variation of PC2, thereby the most important changes in exportable yield differences between varieties are observed in these environments.

'Tullio' and 'Leonardo' varieties are the most extreme in the PC1 and PC2, respectively and therefore the major contributors to the interaction.

The studied environments are grouped into 2 mega environments (Fig. 4). The first consists of the three planting dates of Padre Hurtado, where the 'Tullio' show the largest exportable yield, followed by 'OT782'. The second mega environment groups all Polpaico Santo Domingo and Lampa planting dates, which highlights 'Leonardo' followed by 'Ciro'. both varieties with the highest exportable yield.

Fig. 4 also shows that 'Tullio' is very unstable in Padre Hurtado environments, while 'OT782' showed greater stability. The variety 'CH121' had the lowest yield on the 2 mega environments.

3.2. *Exportable yield and its association with other studied variables.*

Losses associated to diseases were between 16 and 47%, being 'Leonardo' and 'Ciro' the varieties less susceptible to diseases. Compared to sick plants, plants with premature bolting and off-type plants had low impact on the percentage of harvested plants and yield. Moreover the percentage of heads with exportable color was the second most important variable. The exportable color affects directly the exportable yield, which was reduced between 8 and 46% due to this variable. 'Leonardo' and 'OT782' showed the highest percentage of heads with exportable color, 92 and 91%, respectively (Table 3).

Padre Hurtado showed the lowest percentages of sick plants and highest exportable yields, as well as the highest values of exportable yield for all planting dates (Table 4).

In the PCA analysis, from the total variability, 78.4% was explained by the first two principal components (PC1 and PC2), where PC1 explained 56% of the total variability (Fig. 5). The varieties with greater influence, the ones which their projections are more distant from zero are 'CH121' and 'Leonardo'. These two varieties are those with greater differences among themselves, 'Leonardo' is the variety of highest exportable yield and 'CH121' is the one with lowest exportable yield.

Variables percentage of harvested plants, yield and exportable yield are positive and highly correlated. The variable sick plant percentage is positively associated with leaf number at head closing. The premature bolting percentage is positively correlated with the offtype percentage. The sick plant percentage is negatively associated with the harvested plant percentage, yield and exportable yield; affecting more these variables than the premature bolting percentage. On the other hand sick plant percentage and premature bolting percentage were the variables that presented the highest values in varieties 'CH121' and 'OT790' located on the left of the biplot, while harvested plant percentage, yield and exportable yield had the highest values in Chioggia type varieties 'Leonardo' and 'Ciro' located to the right of the biplot. Treviso type variety 'Tullio' had the highest exportable color percentage.

In the principle components analysis of the environments (Fig. 6), 78.2% of the total variability is explained by the first two components. PC1 explains 57% of the total variability. The most extreme environments were Santo Domingo_1 and Padre Hurtado_3, where minor and major exportable yields were achieved respectively. These differences are mainly given by sick plant percentage and leaf number at head closing. Variables yield and exportable yield are negatively correlated with sick plant percentage. Padre Hurtado_1 was the only location that had the lowest sick plant percentage.

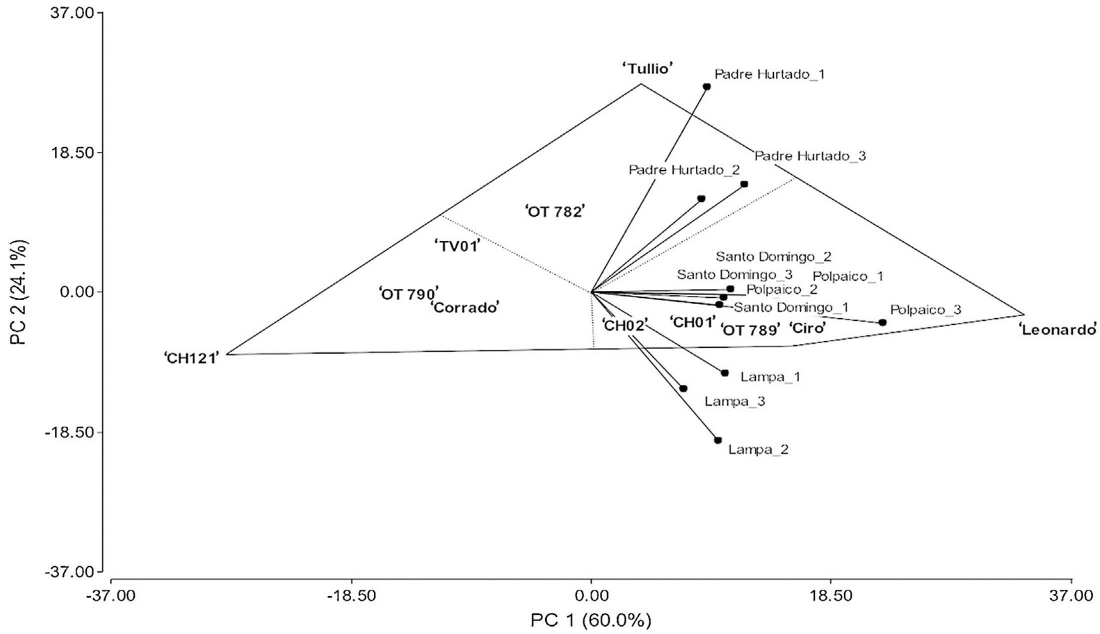

Fig. 4. Biplot from regression model per site (SREG) for the exportable yield of the 11 varieties of radicchio in 12 environments.

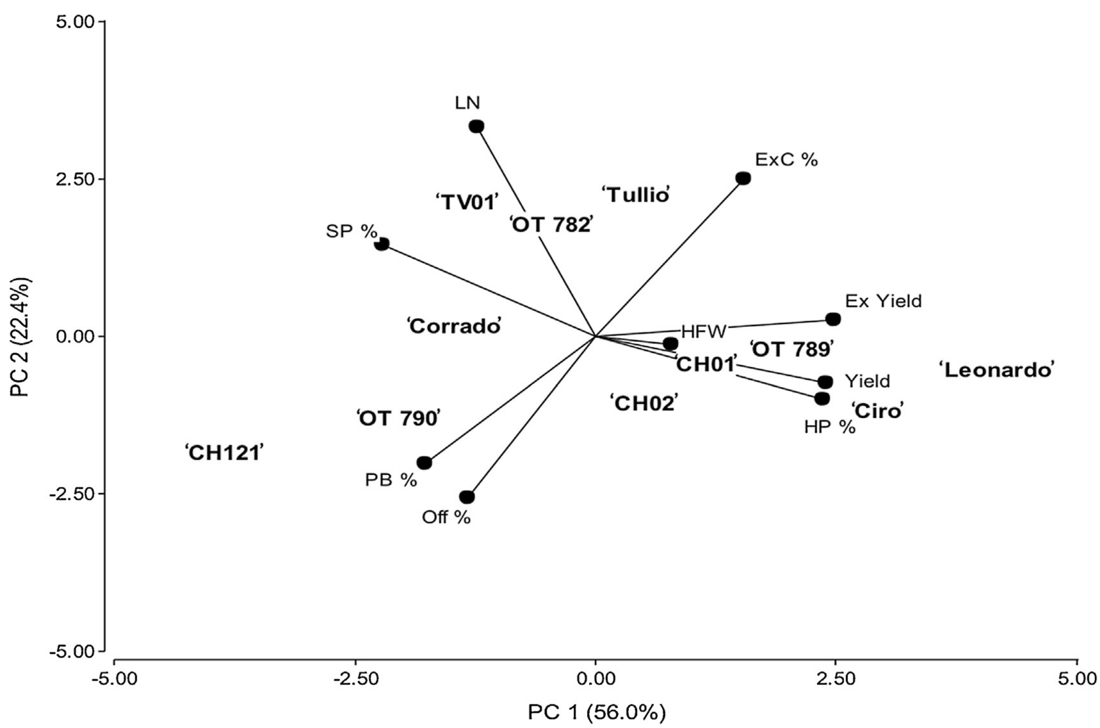

Fig. 5. Principal components analysis of the behavior of 11 radicchio varieties over all measured variables (vectors). Abbreviations used are: harvested plants percentage (HP%), yield (Yield), exportable yield (ExYield), sick plant percentage (SP%), premature bolting percentage (PB%), offtype percentage (Off%), leaf number at head closing (LN), head fresh weight (HFW) and exportable color percentage (ExC%).

4. Discussion

According to the results, there are open-pollinated varieties that can be used as an alternative to 'Leonardo' hybrid variety, due to high exportable yield achieved in the locations evaluated in the Chilean central area. However there is no variety that can be used widely in all environments because the variety with the best performance in one location is not necessarily the best in others. This was proved in combined analysis of variance performed, where G × E interaction was highly significant for exportable yield.

When patterns of interaction were evaluated it was observed that the most important determinant of these patterns was the radicchio type. Chioggia type showed positive interaction with Polpaico, Santo Domingo and Lampa environments. Treviso type had positive interaction with Padre Hurtado environments. Biesiada and Tomczak (2012) observed considerable variation in the proportion of exportable yield on total performance by type and variety of radicchio. 'Leonardo' and 'Tullio' are the varieties that most contributed to the G × E interaction.

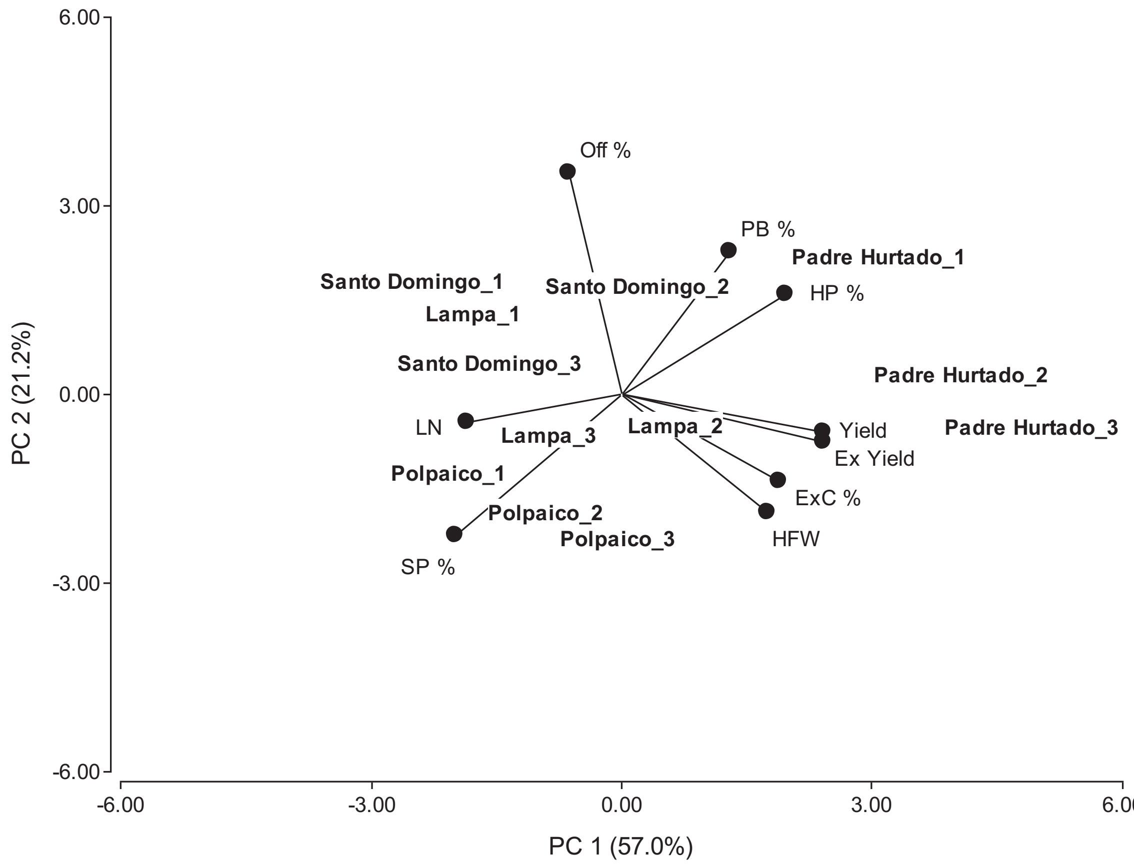

Fig. 6. Principal components of the 12 environment effects in the response of the variables analyzed (vectors) of 11 radicchio varieties. Abbreviations used are: harvested plants percentage (HP%), yield (Yield), exportable yield (ExYield), sick plant percentage (SP%), premature bolting percentage (PB%), offtype percentage (Off%), leaf number at head closing (LN), head fresh weight (HFW) and exportable color percentage (ExC%).

It is possible to exploit the G × E interaction through the selection of varieties which are widely adapted to the locations and avoid interaction by selecting for specific adaptation (Cooper et al., 1996). The only way the G × E interaction can be exploited is dividing environments in mega environments (Yan and Tinker, 2006; Xu et al., 2014). In these trials a clear separation of locations in two mega environments was observed, one determined by Padre Hurtado location and the other by Polpaico, Santo Domingo and Lampa locations (Fig. 4). Mega environments separation is mainly attributable to environmental variables such as mean temperature, mean relative humidity or type of soil.

Varieties considered as widely adapted were Chioggia type, highlighting 'Leonardo' and 'Ciro'; and specific adaptation to Treviso type being the open-pollinated variety 'Tullio' which turned out to have the highest yields for the mega environment consisting of the three planting dates of Padre Hurtado. The variety Chioggia type with major exportable yield was the hybrid 'Leonardo', followed by open-pollinated variety 'Ciro' (Fig. 4). 'Ciro' could be considered as an alternative to 'Leonardo' in the mega environments of Polpaico, Santo Domingo and Lampa locations, due to its high yield and lower cost.

The main causes of the reduction in exportable yield were due to sick plant percentage and exportable color percentage. *Sclerotinia* sp., *Rhizoctonia* sp. and *Erysiphe* sp. caused decreases in exportable yield between 16% and 47%. Similar results were reported by Berlien (2004) and Biesiada and Tomczak (2012). Sick plant percentage had a negative association with exportable yield ($r = -0.83$; $P < 0.01$) and a positive association with leaf number at head closing ($r = 0.73$; $P < 0.05$). Chioggia type varieties 'Leonardo' and 'Ciro' had the lowest number of sick plants, therefore greater disease resistance. Unlike Treviso type varieties, which showed good performance only in environments with low disease percentages, like Padre Hurtado.

The most extreme environments in terms of exportable yield were Santo Domingo_1 y Padre Hurtado_3 where the minor and major exportable yields were achieved respectively. Padre Hurtado environment had the lowest percentages of sick plants percentage, and associated with this, higher exportable yields. While Polpaico and Lampa had the highest sick plants percentage, in Padre Hurtado had lower sick plants percentage due probably to the characteristics of the soils in the area, sandy texture class, recognized as optimum for radicchio (Pimpini, 1990). In addition, Padre Hurtado had the lowest leaf number at head closing which would have allowed better ventilation between rows, avoiding favorable conditions for disease development. It has been seen that narrow rows and high planting density reduces air circulation trapping moisture (Tu, 1997), thereby contributing to the high incidence of *Sclerotinia sclerotium*. A similar effect could be obtained in the canopy with deficient irrigation by applying extended watering times and with high frequency. Another interesting aspect that influence the yield increase, is that Padre Hurtado has higher levels of nitrogen in their soils, due to contributions from Mapocho river, which is rich in nitrates (Silva et al., 2007). Increases in the nitrogen dose of soils with causes significant increases of yields and head weights in radicchio (Biesiada and Kolota, 2008; Biesiada and Kolota, 2010). The Treviso type variety 'Tullio' had the highest head weight, and it was observed in Padre Hurtado.

'Ciro' showed less exportable yield than 'Leonardo' due to lower exportable color percentage (Table 3). The exportable color determines whether a plant is marketable or not (Gazula et al., 2005).

It is known that the quality and exportable yield in radicchio are influenced by numerous factors such as weather conditions, soil moisture, fertilization, planting date, harvest date, radicchio type and variety (Berlien, 2004; Žnidarčič et al., 2004; Monti et al., 2005; Biesiada and Kolota, 2008; Francke and Majkowska-Gadomska, 2008; Devacht et al., 2009; Lucarini et al., 2012).

In this study, the yield decrease obtained from early flowering bolting was insignificant in relation to sick plants percentage and exportable color, however, for many authors (Paulet, 1985; Suhonen, 1991; Grevsen, 1992; Gianquinto, 1997; Žnidarčič et al., 2004) premature flowering bolting is the major cause of yield decrease in radicchio.

Variety 'CH121' showed the lower yields due to the high percentage of sick plants, bolted plants and low percentage of exportable color.

5. Conclusions

There is significant G × E interaction between radicchio varieties, allowing the selection of specific varieties for two mega environments. In Polpaico, Lampa and Santo Domingo mega environment, the Chioggia type variety hybrid variety 'Leonardo' showed the largest exportable yield, however 'Ciro' which is also Chioggia type but an open pollination variety, can be considered a good economic alternative for these locations. In Padre Hurtado mega environments, the Treviso type open-pollinated variety 'Tullio' showed to be an economical alternative. Diseases are the main cause of loss of radicchio exportable yield in the Chilean central area.

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