Acta Physiologiae Plantarum (2021) 43:161
https://doi.org/10.1007/s11738-021-03332-z

ORIGINAL ARTICLE

Evaluation and representation of ethylene effect on vase life and quality of rose (*Rosa hybrida*) cv. Vendela

Felix Baron[1] · **Rolando Mendoza**[1,2] · **Sandra E. Melo**[3] · **Jairo Clavijo**[3] · **Diego A. Castellanos**[1,4]

Received: 15 September 2020 / Revised: 17 February 2021 / Accepted: 1 November 2021

Abstract

In this study, changes in the quality and vase life of cut roses cv. Vendela generated by the presence and influence of ethylene were analyzed and represented. A static experiment was proposed to determine vase life by putting fresh floral stems in hermetic containers and introducing different amounts of ethylene in a range of concentrations from 0 up to 7 μL L^{-1} at 14 °C. The main ethylene response for Vendela roses was the petal abscission. Within the range 0–4 μL L^1 vase life decreases as the ethylene concentration increases. At ethylene concentrations over 4 μL L^{-1}, vase life did not change significantly. The results thus obtained allowed to establish that the flower vase life can be considered as a function of the ethylene concentration in the surrounding atmosphere up to a maximum value (5 μL L^{-1}). From experimental data, a mathematical model to represent the cumulative petal fall (%CPF) as a function of exogenous ethylene was successfully adjusted. By using the above equation and by considering the senescence stage as that corresponding to %CPF = 5% a vase life model was established. The model can satisfactorily represent the vase life of cut Vendela roses at different ethylene concentrations and it constitutes a novel and useful tool that can be used to improve postharvest handling and storage and reduce losses of this type of flower.

Keywords Cut flowers · Deterioration rate · Ethylene · Modeling · Postharvest quality

Introduction

The postharvest vase life of flowers determines its acceptance to the final customers and their market value (Ha et al. 2017; Macnish et al. 2010). Likewise, it determines the limits for the opening of new markets since the maximum distance of transport without incurring significant quality losses will be related to the deterioration time at a defined storage condition (Elhindi 2012; Vehniwal and Abbey 2019). To define the vase life accurately, it is necessary to relate it correctly with changes in certain quality attributes of the cut flower that can be accurately identified and do not depend as much as possible on value judgments that may be subjective (Kondo et al. 1999; Vehniwal and Abbey 2019). The evolution and decay in these quality attributes will depend on intrinsic factors such as physiological maturity and internal metabolic processes and extrinsic factors such as temperature, relative humidity and concentration of gases in the surrounding atmosphere, e.g. ethylene and O_2 (Lippmann et al. 2019). In containers to preserve flowers, it is necessary to have a suitable and continuous air exchange to avoid the CO_2 and ethylene accumulation and O_2 depletion from the plant respiration. Low O_2 concentrations can lead to a fermentative process due to anaerobic conditions. Flower species with low respiration rates have a longer vase life with respect to those species with higher rates due to the lower degradation rate of substrates. The above can be seen in carnation flowers compared with rose. The former has an approximate respiration rate of 300 mL kg^{-1} h^{-1} of CO_2 and vase life aprox. 10–17 days while roses have an average respiration

Communicated by P. K. Nagar.

Diego A. Castellanos
dacastellanose@unal.edu.co

[1] Post Harvest Lab, Facultad de Ciencias Agrarias, Universidad Nacional de Colombia, Carrera 30 Número 45-03, Edificio 500 A, Bogotá, Colombia

[2] Grupo Cundinamarca Agroambiental, Facultad de Ciencias Agropecuarias, Universidad de Cundinamarca, Avenida 15 barrio Berlín, Facatativá, Colombia

[3] Departamento de Agronomía, Facultad de Ciencias Agrarias, Universidad Nacional de Colombia, Bogotá, Colombia

[4] Instituto de Ciencia y Tecnología de Alimentos, Universidad Nacional de Colombia, Bogotá, Colombia

Published online: 13 November 2021

rate of 400 mL kg^{-1} h^{-1} of CO_2 and circa 8–13 days of vase life (In and Lim 2018; Onozaki et al. 2001; Park et al. 2017).

Exposure to ethylene can decrease the vase life of flowers such as rose (In et al. 2017). Ethylene is known as a phytohormone that regulates ripening and senescence in fresh plants. High ethylene concentrations in the container increase the rate of flower senescence (Iqbal et al. 2017). Exogenous ethylene concentrations from 1 up to 10 μL L^{-1} can affect the metabolism and quality of rose (In et al. 2017). At these concentrations, roses express petal wilting, flower or petal abscission and color changes (Borda et al. 2011; Ma et al. 2005). However, senescence effects and decay that is promoted by ethylene action vary between cultivars being more common bud and flower abscission, while other phenomena such as petal and leaf abscission, bud yellowing, and changes in flower color are less frequent (Müller et al. 1998). Ethylene action is usually delayed by inhibitors such as 1-Methylcyclopropene (1-MCP) and silver. The 1-MCP apparently binds irreversibly to ethylene receptors in the cell plant and prevents ethylene from inducing conformational changes (Scariot et al. 2014; Serek et al. 2006; Vehniwal and Abbey 2019). Silver thiosulfate (STS) acts on receptors that contain bound Cu^{++} ions. Its action may be related to the exchange between copper and silver ions in the receptor protein. Once the Ag^{++} ion is bound to a certain receptor, it is apparently blocked and the ethylene does not bind and, therefore, the activation of the signal transduction cascade is prevented (Serek et al. 2006). However, this compound is banned in many regions of the world due to toxicity problems (Scariot et al. 2014).

One of the methods used to measure ethylene sensitivity in fresh plants is based on a continuous gas flow system. This method consists of small chambers (< 4 L) with controlled air, carbon dioxide and/or ethylene inputs. To maintain desirable gas concentrations, inputs should be large enough to avoid interference with natural ethylene production and respiration by the plant (In et al. 2017). To measure gas concentrations into the container, the output can be connected to a gas chromatograph or if it is possible to include a septum where gas samples are extracted to be analyzed. This chamber should be inside a cabinet with temperature control. However, in this case, results are not available in a short time due mainly to the limitations of laboratory equipment because of the large number of experiments required. Also, it is difficult to determine quality parameters of flowers and the measurement can only be done through photographs and image analysis. For that reason, in this work it was decided to make an important methodological change adopting a system without a continuous flow of gases consisting of hermetically sealed chambers where the ethylene concentration in the headspace is defined by injection of a certain amount of ethylene with a known concentration. This change allows replicates to be more economical and practical. Vase life is defined as the time in which the flower maintains its commercial quality (Fanourakis et al. 2016; Macnish et al. 2010; Mallahi et al. 2018). If the available data allow it, mathematical modeling can be performed to predict a change of a quality parameter that defines the shelf-life of a product as a function of time (Kim et al. 2014; Tromp et al. 2012), the former being a deterministic model.

This work aimed to evaluate and represent through modeling the sensitivity and effect of different headspace ethylene concentrations (0–7 μL L^{-1}) over the quality and vase life of rose cv. Vendela. The Vendela variety was selected for this study due to its commercial importance in the farms of the Bogotá savanna and its growing export market in the United States and Europe.

Materials and methods

Plant material

Rose stems cv. Vendela were obtained from a crop field located in Facatativá, west of the savannah of Bogota, Colombia (June–July months, average temperature 18.9 °C, average relative humidity 74.5%, average rainfall of 45 mm), and transported immediately after being harvested to the Post-Harvest Laboratory at The Faculty of Agricultural Sciences of the National University of Colombia (Bogotá, Colombia) at 12 °C. Flowers with visible mechanical damage or excessive floral opening were discarded and flowers with a similar layout (size, physical appearance) were selected to reduce variance. Ten samples were taken to measure the initial flower diameter and CIELAB color of the petals being these 36.74 ± 3.05 mm and $L^* = 89.29 \pm 1.69$, $a^* = -1.70 \pm 1.01$ and $b^* = 16.97 \pm 1.64$ respectively. Floral stems were cut up to 10 cm with a weight of 6.33 ± 0.55 g per stem.

Experimental setup

In this study, a static system was prepared to determine the effect of ethylene concentration over rose quality and vase life. Flowers were put individually in plastic vases with 10 mL of distillate water. Then, three flowers with their respective vases were put in a hermetic acrylic container with an internal volume of 2210 mL (Felli®, Taipei, Taiwan). The container lids were perforated to obtain a circular perforation of 1 cm diameter in which a rubber septum was placed for sampling the internal atmosphere (O_2, CO_2 and ethylene concentrations). In the acrylic containers, there was no gas transfer with the exterior. To measure ethylene sensitivity, a completely randomized experimental design with a factorial arrangement of 12 × 8 was carried out. The first factor was storage time (12 measurement days between days

1 and 15) and the second factor was ethylene concentration (eight concentrations between 0 and 7 μL L^{-1}, varying 1 μL L^{-1} between treatments). Each container with three flowers inside was closed and the necessary volume of a gas with a mixture of 5% (molar fraction) of ethylene and 95% of N_2 (Cryogas®, Medellin, Colombia) was injected through the septa to reach the desired ethylene concentration inside the container. For each ethylene treatment, four replicates ($n = 4$) were prepared to be each of them one container with three individual flowers. After injecting the ethylene mixture, the containers were stored at 14 ± 1 °C. To evaluate the evolution in quality parameters of the samples, all the containers were opened daily during approx. 1 h. After the quality measurements were measured (as indicated below), the containers were closed hermetically again, and a new mixture of ethylene was introduced to renovate the initial internal atmosphere. Then, containers were stored again at 14 °C continuing the trials.

To estimate the endogenous ethylene generation from the Vendela roses, the experiments performed at 0 μL L^{-1} of ethylene initially in the container were used to determine the ethylene production rate.

Ethylene production rate measurement

Samples of 1 mL of headspace gas in the containers were taken with a syringe through the rubber septa and immediately analyzed in an Agilent 7890A gas chromatograph (Agilent Technologies Inc., Santa Clara, CA, USA). The analysis conditions were similar to those used by Mendoza et al. (2016). The chromatographic details were as follows: injector temperature: 70 °C, oven temperature: 50 °C, FID detector temperature 250 °C, and helium as a carrier gas with a flow of 7.0 mL min^{-1}). The chromatographic method was calibrated by using a 101-μL L^{-1} ethylene patron nitrogen base (Linde Colombia S.A., Bogotá, Colombia). This gas was mixed with nitrogen (Linde Colombia S.A., Bogotá, Colombia) to obtain different concentrations in the range of 0–10 μL L^{-1}.

To calculate the ethylene production rate (r_{C2H4}) from the cut flowers in the acrylic containers, the following equation was used:

$$r_{C_2H_4} = \frac{V\left(C_{C_2H_4}\right)}{W\Delta t}\left[\frac{\mu L}{kg\ h}\right], \tag{1}$$

where V is the volume of the container headspace in L, $C_{C_2H_4}$ is the ethylene concentration measured by gas chromatography (μL L^{-1}), W is the weight of the flowers (kg) and Δt is the time between closing the lid of the container and taking the sample to inject into the chromatograph (h). Equation 1 refers to the ethylene production rate per unit of mass and per unit of time. Considering the ethylene production is generated both in the flower and in the stem all the samples were cut at a height of 10 cm which is not a commercial height. The above should be considered to scale or replicate the results of this work.

Respiration rates and respiratory quotient

To estimate the flower respiration (O_2 consumption and CO_2 production), the changes in O_2 and CO_2 concentrations were measured inside the acrylic container. 5 ml of gas was taken out and sampled with an Oxybaby® 6i electronic gas analyzer (Witt-Gasetechnik GmbH & Co. KG, Witten, Germany) and the results were expressed in percentage (ml of gas per every 100 ml of gas headspace). The O_2 and CO_2 production rates were calculated as follows (Mendoza et al. 2016):

$$r_{O_2} = -\frac{V\left(C_{O_2} - C_{O_{2_0}}\right)}{W\Delta t}\left[\frac{\mu L}{kg\ h}\right], \tag{2}$$

$$r_{CO_2} = \frac{V\left(C_{CO_2} - C_{CO_{2_0}}\right)}{W\Delta t}\left[\frac{\mu L}{kg\ h}\right], \tag{3}$$

where V is the volume of the container headspace in mL, C_{O_2} and C_{CO_2} are the oxygen and carbon dioxide concentration measured in the headspace (mL gas per 100 mL gas headspace), $C_{O_{2_0}}$ and $C_{CO_{2_0}}$ are the oxygen and carbon dioxide concentration in the normal atmosphere, W is the weight of the flowers (kg), n is the number of flowers in the container (three flowers) and Δt is the time between closing the lid of the container and taking the sample to measure gas concentrations (h).

The respiratory quotient (RQ) was calculated as the ratio between carbon dioxide production and oxygen consumption rates (Sousa et al. 2017):

$$RQ = \frac{r_{CO_2}}{r_{O_2}}. \tag{4}$$

Quality parameters

The color was measured in the external rose petals by using a Minolta ChromaMeter (Model CR-331, Minolta Camera Co., Osaka, Japan) in the CIELAB color space coordinates L^*, a^* and b^*. A standard illuminant, 'Daylight 65', was considered. The color change ΔE was calculated as follows:

$$\Delta E = \sqrt{(\Delta L^*) + (\Delta a^*) + (\Delta b^*)}, \tag{5}$$

where ΔE is the total color change and ΔL^*, Δa^* and Δb^* are the differences in each color coordinate measured in each day compared to day zero.

The floral opening was measured as the distance between the external petals and represents the flower diameter. Measurements of floral opening were taken by using a Proster® Digital Vernier Caliper model 7874 In8 (HongKong Proster Trading Ltd., GuangZhou, China).

Petal fall was measured by counting the number of petals detached from the floral head. Petal fall was expressed as the cumulative percentage of petals fallen (% CPF).

Statistical analysis and modeling

A one-way ANOVA analysis was applied, and a Tukey test ($p \leq 0.05$) was used to determine significant differences between the means of the measured characteristics (respiration rates and quality parameters) for the different treatments. Vase life in the samples was represented by using a deterministic method based on finding a mathematical function that relates a quality parameter who defines vase life (in this case petal abscission) with storage conditions. Considering the above, a logistic model was used to correlate the cumulative percentage of petals fallen and the storage time as follows (Sierra et al. 2019):

$$\%\mathrm{CPF} = \frac{1}{1 + e^{-C_1(t - C_2)}}, \quad (6)$$

where % CPF is the cumulative percentage of petals fallen, t is the storage time (days), C_1, and C_2 are the regression parameters that were found using the least-squares method. For parameters that are dependent on ethylene, a model based on a first-order chemical reaction kinetic was used (Sierra et al. 2019):

$$C_\mathrm{i} = C_\mathrm{iEQ} + \left(C_\mathrm{io} - C_\mathrm{iEQ}\right)e^{-C_\mathrm{ET}k_\mathrm{i}}, \quad (7)$$

where C_io, C_iEQ and k_i are the adjustment parameters and C_ET is the ethylene concentration in the atmosphere surrounding the flowers.

Vase life

For this study vase, life was defined as the time elapsed until a visible deterioration of the flower. Petal abscission (more than 5% of petals fallen) was used as a senescence criterion for rose cv. Vendela. From Eqs. 6 and 7, the time corresponding to vase life was isolated taking into account the above.

Results

Postharvest physiological behavior of Vendela roses

Figure 1 shows the ethylene production rate as a function of storage time. Ethylene production rate by Vendela roses varied between 0.08 and 0.39 μL kg^{-1} h^{-1} (1.60 and 6.63 nL flower^{-1} h^{-1}). Similar data have been found for 'Kordana', 'Parade' (Müller et al. 1998), and 'Peckoubo' varieties (Borda et al. 2011). Ethylene production decreased until the sixth day of storage, and after that, increased up to the eighth day of storage and remained approx. steady until day 13 of storage. On day 14, ethylene production increased due possibly to flower senescence. It was evidenced in the petal fall from day 13.

Figure 2 shows O_2 consumption and CO_2 production rates as a function of storage time. In general, respiration rates decreased over time possibly due to the reduction of carbohydrate reserves in the flower and/or a carbohydrate transport decrease within the flower (Monteiro et al. 2002). A similar trend was found for cut flowers of lotus (Salaemae

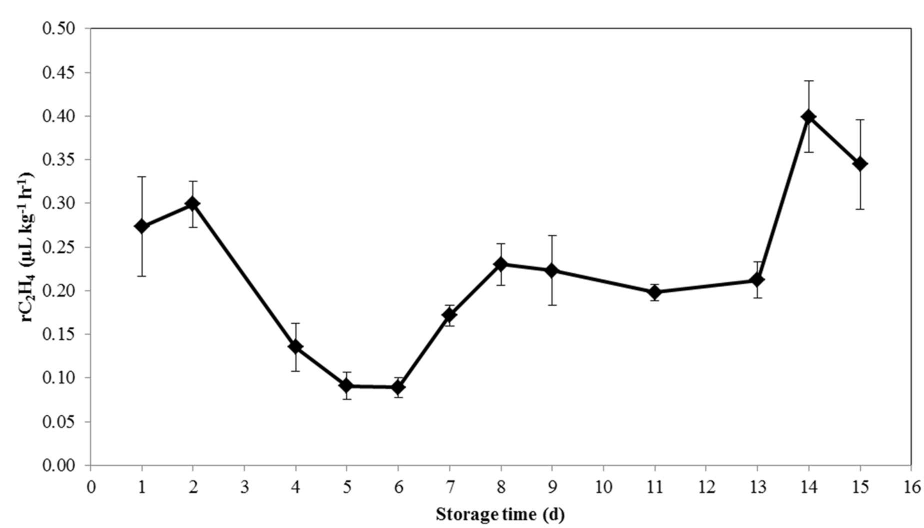

Fig. 1 Ethylene production rate by Vendela roses stored at 14 °C. Bars represent standard deviation (SD) of 4 replicates

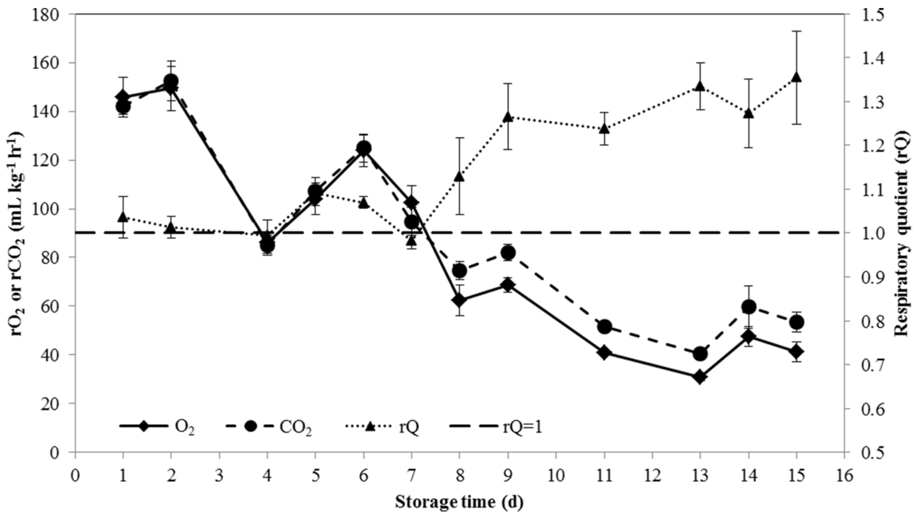

Fig. 2 Oxygen consumption (r_{O_2}) and carbon dioxide production (r_{CO_2}) rates, and respiratory quotient (RQ) of Vendela roses stored at 14 °C. Bars represent SD of four replicates

et al. 2018). Likewise, from day eight the CO_2 production rate was greater than the O_2 consumption rate coupled with the increase of ethylene production indicating a possible symptom of stress. This behavior shows that respiration process loses efficiency and flowers take down subtracts other than carbohydrates.

Effects of exogenous ethylene exposure and vase life

For Vendela roses, exposure to exogenous ethylene present differences with the treatments without application of exogenous ethylene, mainly in petal abscission. Floral opening (Fig. 3) started on the first day and finished on the fifth day. Statistical differences can be noticed only on the fifth day of storage. On that day, the value of floral opening increased for treatments up to 3 μL L^{-1}. At higher ethylene concentrations, the floral opening decreased. On day 5, floral opening for 7 μL L^{-1} was lower respecting the treated samples with the threshold concentration of 3 μL L^{-1}. From this concentration, ethylene inhibits floral opening. The response of the floral opening to the action of ethylene has been documented as dependent on the variety (Tan et al. 2006). However, flower opening can be reliant on exogenous ethylene concentrations for the same cultivar.

Figure 4 shows that the time in which petal fall begins can be considered function of ethylene concentration. At an ethylene concentration of 7 μL L^{-1}, petal fall begins at the day 6 of storage while with no exogenous ethylene, the falling of petals begins at 13 days of storage. Similar results were found by Hegelund et al. (2017). As the petal abscission is the first symptom of ethylene sensitivity, this can be considered a criterion to define the vase life of Vendela roses.

Figure 5 shows the O_2 consumption rate of Vendela roses at different exogenous ethylene concentrations. There were no differences between treatments until 7th day of storage where at an exogenous ethylene concentration of 7 μL L^{-1} the O_2 consumption rate increased up to 145.2 mL kg^{-1} h^{-1},

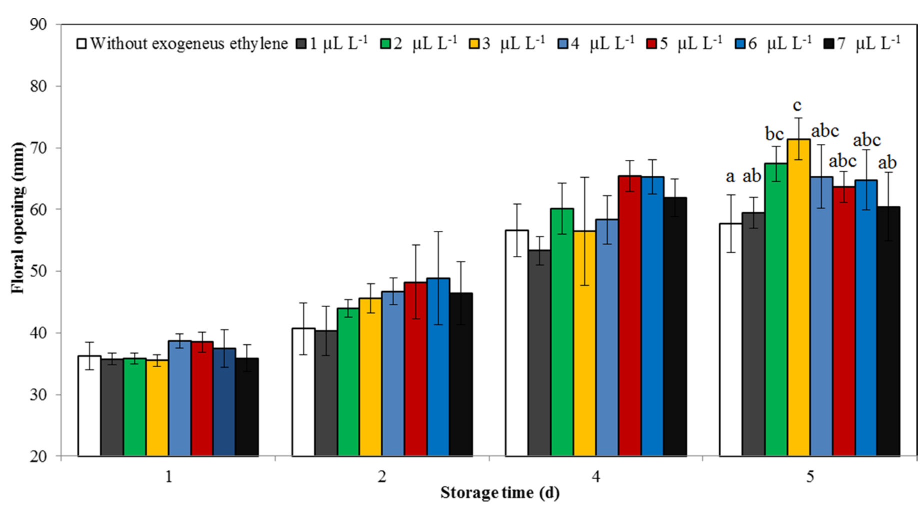

Fig. 3 Floral opening of Vendela roses stored at 14 °C depending on exogenous ethylene concentration. Bars represent SD of four replicates

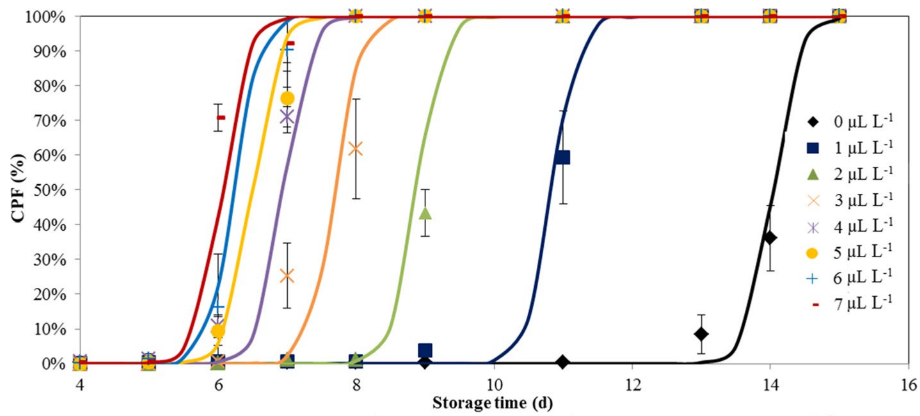

Fig. 4 Petal abscission (cumulative percentage of fallen petals, %CPF) of Vendela roses stored at 14 °C depending on exogenous ethylene concentration. Continuous line represents the logistic model for each ethylene concentration. Bars represent SD of four replicates

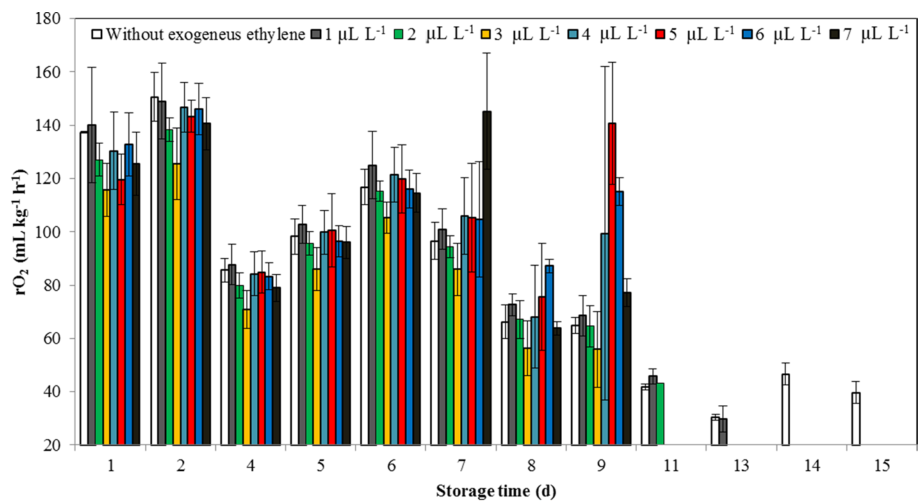

Fig. 5 Oxygen consumption rate (r_{O_2}) of Vendela roses at different exogenous ethylene concentrations and 14 °C. Bars represent SD of four replicates

while for the other treatments, the O_2 consumption rate increased only up to 99.1 mL kg^{-1} h^{-1}. At 8th day of storage, there was a significant increase in the O_2 consumption rate at an exogenous ethylene concentration of 6 µL L^{-1} compared to the other treatments. A similar increase of O2 consumption rate was observed for the day 9th of storage with an exogenous ethylene concentration of 5 µL L^{-1}. Figure 6 shows the RQ increased from the day 8 of storage for all treatments; therefore, exogenous ethylene did not influence the moment when the RQ changes. However, at that time, ethylene promotes the use of substrates other than carbohydrates for respiration. As shown in Table 1, RQ increases at day 8 of storage for exogenous ethylene concentrations above 2 µL L^{-1} reaching a maximum value at a concentration of 4 µL L^{-1}. Table 1 shows the corresponding RQ to the respective vase life and differences between low and high ethylene concentrations have been noticed. The RQ is greater than 1.0 at exogenous ethylene concentrations below 4 µL L^{-1} and close to 1.0 above 4 µL L^{-1}. This may be explained considering that the vase life of flowers at high concentrations of exogenous ethylene ran out before the RQ ratio increased, suggesting that simple carbohydrates remain the main source of energy. On the other hand, flowers stored at low concentrations of exogenous ethylene (less than 3 µL L^{-1}) depleted their carbohydrate reserves before their vase life was finished. Data also show that exogenous ethylene may influence flower metabolism at concentrations lower than 1 µL L^{-1} and that at concentrations above 4 µL L^{-1} this influence becomes smaller. Color change (ΔE) in petals is more accentuated at high concentrations of exogenous ethylene demonstrating that ethylene increased susceptibility to wilt and could be a factor to increased deterioration due fungal spoilage (Scariot et al. 2014; Williamson et al. 2018). In some floral species, senescence is evidenced by petal abscission, wilting, or even wilting followed by abscission (Shahri and Tahir 2011).

Modeling vase life

To represent vase life as a function of an extrinsic factor such as exogenous ethylene, a relationship between the cumulative percentage of petals fallen and storage

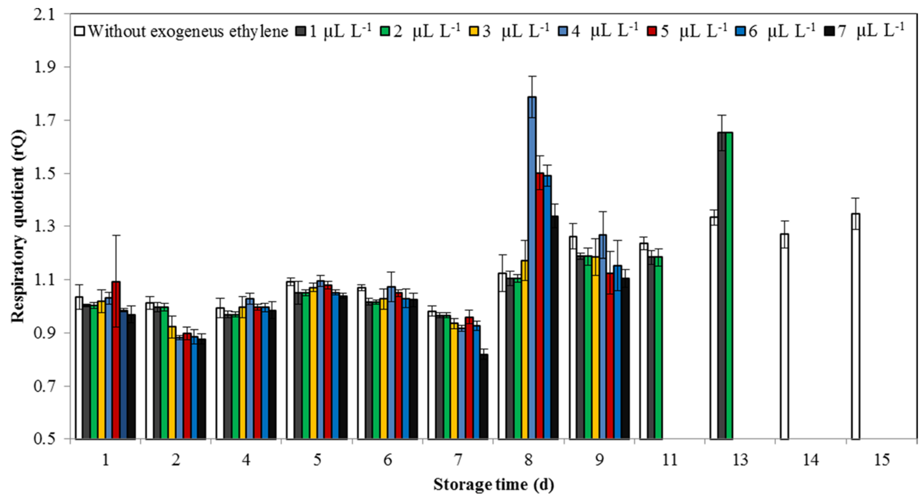

Fig. 6 Respiratory quotient (RQ) of Vendela roses at different exogenous ethylene concentrations and 14 °C. Bars represent SD of four replicates

Table 1 Vase life of *Vendela* roses, final respiratory quotient (RQ) and total color change (ΔE) as function of exogenous ethylene concentration at 14 °C

Exogenous ethylene concentration	Vase life (*d*)		Respiratory quotient (RQ)**		ΔE
	Experimental	Modeled (Eq. 9)	At day 8 of storage	At the time of vase life	
No exogenous ethylene	14.0 ± 0.8a*	13.5	1.12 ± 0.07a*	1.26 ± 0.09ab	2.21 ± 0.63a
1 μL L^{-1}	10.5 ± 1.0b	10.3	1.10 ± 0.03a	1.18 ± 0.04ac	2.12 ± 0.50a
2 μL L^{-1}	9.0 ± 0.0c	8.3	1.10 ± 0.01a	1.15 ± 0.04abc	2.43 ± 0.56a
3 μL L^{-1}	7.8 ± 1.0cd	7.2	1.17 ± 0.07ab	1.02 ± 0.12c	3.28 ± 0.29a
4 μL L^{-1}	6.5 ± 0.6de	6.4	1.79 ± 0.08d	1.00 ± 0.10cd	4.10 ± 0.60ab
5 μL L^{-1}	6.5 ± 0.6de	6.0	1.50 ± 0.06cd	1.00 ± 0.07cd	7.31 ± 0.38b
6 μL L^{-1}	6.5 ± 0.6de	5.7	1.49 ± 0.04cd	0.99 ± 0.07cd	8.05 ± 1.17bc
7 μL L^{-1}	6.0 ± 0.0e	5.5	1.34 ± 0.04bc	1.02 ± 0.03d	9.98 ± 1.98c

*Means with different letters across are significantly different at $p \leq 0.05$ by the Tukey's HSD test. Standard deviation (SD) included for four replicates

**Respiratory quotient ($/r_{O_2}$) measured at the final day of vase life

time was established by using logistic regressions. As shown in Fig. 4, logistic regressions provide a good fit of experimental data. An ANOVA of the C_1 parameter of Eq. 6 shows that there is no difference between treatments; this suggests that when the petals begin their fall, they do so at the same rate independent of the exogenous ethylene concentration. C_2 in Eq. 6 represents the time when 50% of petals fall (t_{50}) and significant differences for the C_2 parameter were found at low ethylene concentrations. This difference decreases as the ethylene concentration increases up to 5 μL L^{-1}. From this concentration, there are no significant differences between treatments. To define the relationship between the C_2 parameter and ethylene concentrations, Eq. 7 was used resulting in the following:

$$C_2 = C_{2EQ} + \left(C_{2o} - C_{2EQ}\right) e^{-C_{ET} k}, \tag{8}$$

C_{2o} corresponds to the value of C_2 when the exogenous ethylene concentration is zero, whereby is the maximum t_{50}. C_{2EQ} is the value at an infinite ethylene concentration and k parameter denotes a specific rate constant. Table 2 shows the parameters calculated for Eqs. 6 and 8.

After performing the regressions, t_{50} for an exogenous ethylene concentration of 0 μL L^{-1} was estimated as 14.03 days while for 0.5 μL L^{-1}, the t_{50} value is 12.24 days decreasing by 13%. For flowers of *Rosa bourboniana* cv. *Gruss an Teplitz*, the time required for petal abscission for the control (without ethylene) was 1.29 ± 0.08 days, while flowers submitted at 0.5 μL L^{-1} of exogenous ethylene required 0.73 ± 0.04 days for petal abscission (Sane et al. 2007) decreasing the time for petal abscission by 45%. Petal abscission is, therefore, a characteristic of the

Table 2 Estimated parameters of accumulative percentage of petals fallen (% CPF) by logistic equation

C_1 parameter*	
C_1 (d^{-1})	5.53 ± 1.93
C_2 parameter (d)**	
No exogenous ethylene	14.07 ± 0.48[(a)]
1 μL L^{-1}	10.59 ± 0.51[(a)]
2 μL L^{-1}	9.06 ± 0.12[(a)]
3 μL L^{-1}	7.60 ± 0.71[(b)]
4 μL L^{-1}	6.71 ± 0.18[(bc)]
5 μL L^{-1}	6.71 ± 0.18[(bc)]
6 μL L^{-1}	6.45 ± 0.33[(c)]
7 μL L^{-1}	5.84 ± 0.03[(c)]
C_2 regression parameters	
C_{2o} (d)	14.03 ± 0.48
C_{2EQ} (d)	5.79 ± 0.93
k (L μL^{-1})	0.49 ± 0.05
R^2	0.985

Standard deviation (SD) included

SD included for four replicates

[a]C1 does not present significant differences between treatments

[b]Means with different letters across are significantly different at $p \leq 0.05$ by the Tukey's HSD test

rose cultivar. The above can suggest that for the Vendela cultivar, there is no suppression of ethylene pathway genes since transcript accumulation of most ethylene biosynthesis genes increases in petal abscission (Singh et al. 2019).

Table 1 shows vase life as a function of ethylene concentration. Although the deterioration of roses increases at ethylene concentrations above 3 μL L^{-1}, it does more slowly. For ethylene concentrations of 4 μL L^{-1} up to 7 μL L^{-1} vase life did not have a significant difference. At an ethylene concentration of 7 μL L^{-1}, the vase life of Vendela roses is reduced down to 54%, whereby this variety can be classified as highly sensitive to ethylene (In et al. 2017). Without exogenous ethylene, the sample's vase life was 14.0 ± 0.8 days while at an exogenous ethylene concentration of 1 μL L^{-1}, vase life takes a value of 10.5 ± 1.0 days. Similar values for vase life of rose cv. Vendela have been reported by Macnish et al. (2010).

By using the model described with Eqs. 6 and 8, it was possible to represent the cumulative percentage of fallen petals (% CPF) as a function of exogenous ethylene. As shown in Fig. 4, predicted % CPF is close to experimental data for the different ethylene concentrations. As mentioned before, the cumulative petal fall has a logistic behavior with a rapidly increasing interval and then a steady-state, from the predicted % CPF and the associated equations it was possible to define a predicted vase life by taking as a limit to flower rejection an %CPF = 5%. In this way, the vase life equation is presented as follows:

$$t_{VL} = \frac{1}{C_1}\ln\left(\frac{1-5\%}{5\%}\right) + \left(C_{2EQ} + \left(C_{2o} - C_{2EQ}\right)e^{-C_{ET}k}\right), \tag{9}$$

where t_{VL} represents the vase life of rose cv. Vendela. Equation 9 represents a deterministic model to describe vase life as a function of exogenous ethylene concentration. The predict vase life as a function of exogenous ethylene concentration is shown in Table 2. Predicted data are satisfactorily close to the observed experimental data as shown in Table 2 for the different exogenous ethylene concentrations. This is due to the high degree of correlation between the ethylene concentration present in the medium and the petal fall in the flower.

The static system to evaluate the vase life of cut roses

Figure 7 presents the O_2 profile in the headspaces of the hermetic containers without exogenous ethylene application. O_2 concentration profile is linear in all the treatments, with R^2 values close to 1.0. At the oxygen concentrations achieved, there was no influence of carbon dioxide on the oxygen consumption rate, with it constant throughout the entire measurement interval. The minimum O_2 concentration achieved throughout the experiment is 10% being a limit concentration. O_2 concentrations lower than 10% may induce deviations in the calculation of ethylene and respiration rates (González-Buesa and Salvador 2019). This value can be used as a parameter to configure the static system, mainly the mass of plant material/headspace ratio.

Discussion

In climacteric produce, there are peaks of ethylene production and respiration during ripening (Chen et al. 2018). This behavior is not present for Vendela roses, so it supports the hypothesis that this cultivar is not climacteric. However, in other studies, a climacteric behavior for rose cultivars was found (Müller et al. 1998, 2000) which can indicate that climacteric behavior depends on the cultivar and it is not a universal characteristic of specie. Cutting, handling, and transport (first peak at the second day of storage), changes in respiration pattern (eighth day of storage), and wilting (day 14 of storage) may be responsible for the maximum peaks of ethylene production by Vendela roses.

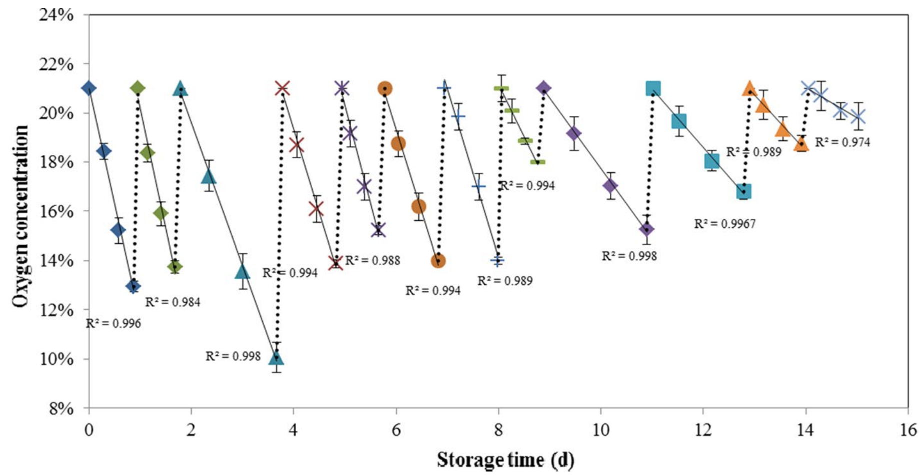

Fig. 7 Oxygen concentration profile of treatments without exogenous ethylene application. Bars represent SD of four replicates

It is noticed that the respiratory quotient, RQ, changes for all treatments at day 8 of storage, and this change is accentuated by exogenous ethylene presence. For this time, the flower begins the degradation of its cellular structures to obtain energy, leading to the use of carbohydrate reserves and proteins as substrates of respiration, which promotes the acceleration of wilt (Ichimura 1998; Teixeira 2016). Stress may induce the use of substrates other than carbohydrates even if there is the availability of sugars in the hydration solution (Teixeira 2016). Ethylene presence induces an increase of respiration rate at the same storage time although the general trend is decreasing as the storage time advances. An increase in the respiration rate due to a rich-ethylene atmosphere implies a high consumption of respiration subtracts and contributes to the onset of stress. The last peak of ethylene production at day 13 of storage coincided with the petal abscission; this suggests that ethylene plays a fundamental role in this phenomenon. The above is reinforced by the fact that the time in which the abscission of petals appears is a function of exogenous ethylene concentration.

Several studies have recognized the effects of ethylene on the vase life of cut roses (Gil et al. 2020; Khatami et al. 2020; Ma et al. 2005). Even, the presence of ethylene in the preharvest stage induces an increase in the rate of ethylene production and, therefore, accelerates the senescence of roses (Gong et al. 2018). Ethylene effects in the acceleration of senescence are mainly early fall of petals and color change due to wilting. Also, it is known that the physiological behavior of rose and its response to exogenous ethylene are strongly dependent on the cultivar (In and Lim 2018). However, to establish an optimal condition for storage and transport of cut roses, additional information related to the relationship between storage parameters and physiological behavior is required. This relationship can be satisfactorily represented through modeling. Time and temperature are usually considered as the most important variables to develop a mathematical model to represent the shelf life of fresh products such as rose. To model shelf life, it is necessary to find quality properties related to this such as petal and foliage color, visible fungal spoilage, petal fall, floral opening, or volatile content; these properties can be measured to develop a kinetic model that can be used to describe vase and shelf life based on environmental conditions. The parameters of these models can be related to temperature by using the Arrhenius equation (Tromp et al. 2012). Likewise, it is also possible to develop other models from the empirical correlation between measurable physiological variables such as respiration or transpiration and the vase life depending on external conditions (In et al. 2016). For this study, for example, an increase was observed in the respiration rate and the RQ ratio indicating the beginning of decay for the cut roses. The above was also described by the vase life model (Table 2). Considering this, by monitoring the O_2 or CO_2 concentrations in the container during the storage, the vase life of the roses as a function of exogenous ethylene can be represented.

There are multiple factors related to technical conditions that affect postharvest quality. Transport or storage temperature, transport times, and additives' doses can be controlled between certain intervals. Depending on these factors, flowers express different physiological behaviors related to their senescence process. However, floriculture industry faces different problems to establish the relationships between controlled variables, physiological behavior, and quality parameters and thus, to determinate this relationship is not easy due to a large number of parameters involved and the variation of these parameters along with the transport, storage, and marketing chain (Macnish et al. 2010). The above makes it more complex to establish a mathematical relationship that includes all the influential parameters in vase life of cut flowers. In this study, from the experimental behavior of Vendela roses exposed to different exogenous ethylene concentrations a vase life model was adjusted from a quality parameter such as petal fall. This model relates the rose vase life to the concentration of exogenous ethylene. These kinds of models are a useful tool for both the design of storage or transport systems and the prediction of vase life for defined postharvest processes.

One of the greatest difficulties for the flower production industry is not having a standard and simple methodology to obtain relationships between flower quality and handling and storage parameters. Usually, each farm develops its method to evaluate flower vase life and results generally are not comparable. Flowers can be treated with an active compound (antifungal, moisturizing, nutritional, ethylene regulator and so) at different doses and stored in containers with temperature and humidity control for a certain time, simulating a transport between the crop field and the final consumer. Simulated transport tries to represent the real transport conditions as much as possible (Pouri et al. 2017). In these simulations, usually, flowers are taken out of the container after the simulated transport time, considering the product must be transferred to another container or inspections have to be carried out. Then, flowers are put in vases to measure longevity (Ichimura and Shimizu-Yumoto 2007). However, inside the container, the temperature and relative humidity have fluctuations and the gas concentrations (O_2, CO_2 and ethylene) are unknown. Therefore, there will be high variability or high uncertainty in the results. Laboratory tests provide better control over quality parameters and, therefore, variability and uncertainty can decrease to acceptable levels. The method used in this work can be a useful proposal to evaluate vase life in cut flowers. This static system provides advantages related to a large number of test and replicates that can be performed in a relatively short time respecting an open continuous system where is difficult to perform a large number of trials at the same time due to equipment limitations. To control gas concentrations in the headspace of a continuous system, it requires reliable flow control equipment and huge amounts of gases (O_2, CO_2, and ethylene) what makes it an expensive system. All this investment in equipment and materials seeks to maintain constant gas concentrations and reduce uncertainty. In the static system, flowers generate ethylene and CO_2 and consume O_2 via respiration depending on the concentration of these gases which will be changing over time which makes it possible to estimate consumption and emission kinetics as a function of gas levels in the system headspace. However, for fresh plants, oxygen is a substrate for ethylene synthesis, and ethylene production rates depend on oxygen concentration (Mendoza et al. 2016). Similar behavior can be found in respiration rates in which specific rates of oxygen consumption and carbon dioxide production exhibit uncompetitive inhibition due to carbon dioxide and gas profiles are curved, mainly at low oxygen concentrations (Castellanos et al. 2017).

Conclusions

Cut roses (*Rosa hybrida*) cv. Vendela did not present a clear climacteric behavior; however, it is a highly ethylene-producing flower and its emission peak can depend mainly on the stress to which the flower is exposed. Vendela cut roses are susceptible to the action of exogenous ethylene and petal abscission is the main effect. Although ethylene did not accelerate the moment in which RQ begins to decrease, it does accentuate its effect. Also, exogenous ethylene contributes to the color change of the petals since it promotes the death of tissue and the consequent appearance of fungal spoilage. The sensitivity of the flower to ethylene is a function of the exogenous ethylene concentration, given the relationship between ethylene dose and vase life, where sensitivity is observed from 1 $\mu L\ L^{-1}$ being maximum from 4 $\mu L\ L^{-1}$. This relationship can be successfully represented with a mathematical model through the % CPF.

The results obtained show that the closed system method can be suitable to measure the effect of exogenous ethylene on the flower and, therefore, it can be a valuable tool for vase life measurement.

Author contribution statement FB carried out the experimental tests and participated in the data analysis. R. Mendoza participated in the experimental tests, data analysis and manuscript construction. SM participated in the data analysis and in obtaining the models. JC participated in the experimental design and data analysis, and DC participated in the analysis of the data and the manuscript construction and writing.

Acknowledgements The authors wish to thank the support provided by the National University of Colombia, University of Cundinamarca and the Foundation for the Promotion of Research and Technology and the Colombian Administrative Department of Science, Technology and Innovation—COLCIENCIAS with its Doctoral Scholarships Program (Convocation number 567/2012) and its program of Postdoctoral Research Fellowships (Convocation number 784/2017).

Funding This study was conducted with funding from Colombian Administrative Department of Science, Technology and Innovation – COLCIENCIAS with its Doctoral Scholarships Program (Convocation number 567) and from the National University of Colombia with its support to graduate research projects (Hermes project 50970).

Availability of data and material The datasets and supplementary material generated and/or analysed during the current study are available from the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Conflicts of interest The authors declare that they have no conflict of interest to disclose. This article does not contain any studies with human participants or animals performed by any of the authors.

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication All authors agree with the contents of the manuscript and its submission to *Acta Physiologiae Plantarum.*

References

Borda AM, Clark DG, Huber DJ, Welt BA, Nell TA (2011) Effects of ethylene on volatile emission and fragrance in cut roses: The relationship between fragrance and vase life. Postharvest Biol Technol 59(3):245–252. https://doi.org/10.1016/j.postharvbio.2010.09.008

Castellanos DA, Mendoza R, Gavara R, Herrera AO (2017) Respiration and ethylene generation modeling of "Hass" avocado and feijoa fruits and application in modified atmosphere packaging. Inter J Food Prop 20(2):333–349. https://doi.org/10.1080/10942912.2016.1160921

Chen Y, Grimplet J, David K, Castellarin SD, Terol J, Wong DCJ, Luo Z, Schaffer R, Celton JM, Talon M, Gambetta GA, Chervin C (2018) Ethylene receptors and related proteins in climacteric and non-climacteric fruits. Plant Sci 276:63–72. https://doi.org/10.1016/j.plantsci.2018.07.012

Elhindi KM (2012) Evaluation of several holding solutions for prolonging vase-life and keeping quality of cut sweet pea flowers (*Lathyrus odoratus* L.). Saudi J Biol Sci 19(2):195–202. https://doi.org/10.1016/j.sjbs.2011.12.001

Fanourakis D, Giday H, Li T, Kambourakis E, Ligoxigakis EK, Papadimitriou M, Strataridaki A, Bouranis D, Fiorani F, Heuvelink E, Ottosen CO (2016) Antitranspirant compounds alleviate the mild-desiccation-induced reduction of vase life in cut roses. Postharvest Biol Technol 117:110–117. https://doi.org/10.1016/j.postharvbio.2016.02.007

Gil CS, Lim ST, Lim YJ, Jung KH, Na JK, Eom SH (2020) Volatile content variation in the petals of cut roses during vase life. Sci Hortic 261:108960. https://doi.org/10.1016/j.scienta.2019.108960

Gong B, Huang S, Ye N, Yuan X, Ma H (2018) Pre-harvest ethylene control affects vase life of cut rose 'Carola' by regulating energy metabolism and antioxidant enzyme activity. Hortic Environ Biotechnol 59(6):835–845. https://doi.org/10.1007/s13580-018-0053-8

González-Buesa J, Salvador ML (2019) An Arduino-based low cost device for the measurement of the respiration rates of fruits and vegetables. Comput Electron Agric 162(March):14–20. https://doi.org/10.1016/j.compag.2019.03.029

Ha STT, In B, Choi H, Jung Y, Lim J (2017) Assessment of pretreatment solutions for improving the vase life and postharvest quality of cut Roses (*Rosa hybrida* L. 'Jinny'). Flower Res J 25(3):101–109. https://doi.org/10.11623/frj.2017.25.3.02

Hegelund JN, Lütken H, Müller R (2017) Postharvest physiology: ethylene in roses. Ref Module Life Sci. https://doi.org/10.1016/b978-0-12-809633-8.05082-2

Ichimura K (1998) Improvement of postharvest life in several cut flowers by the addition of sucrose. Japan Agric Res Q 32:275–280

Ichimura K, Shimizu-Yumoto H (2007) Extension of the vase life of cut roses by treatment with sucrose before and during simulated transport. Bull Natl Inst Floric Sci 7:17–27

In B-C, Lim JH (2018) Potential vase life of cut roses: Seasonal variation and relationships with growth conditions, phenotypes, and gene expressions. Postharvest Biol Technol 135:93–103. https://doi.org/10.1016/j.postharvbio.2017.09.006

In BC, Inamoto K, Doi M, Park SA (2016) Using thermography to estimate leaf transpiration rates in cut roses for the development of vase life prediction models. Hortic Environ Biotechnol 57(1):53–60. https://doi.org/10.1007/s13580-016-0117-6

In BC, Ha STT, Lee YS, Lim JH (2017) Relationships between the longevity, water relations, ethylene sensitivity, and gene expression of cut roses. Postharvest Biol Technol 131:74–83. https://doi.org/10.1016/j.postharvbio.2017.05.003

Iqbal N, Khan NA, Ferrante A, Trivellini A, Francini A, Khan MIR (2017) Ethylene role in plant growth, development and senescence: interaction with other phytohormones. Front Plant Sci 8:1–19. https://doi.org/10.3389/fpls.2017.00475

Khatami F, Najafi F, Yari F, Khavari-Nejad RA, Takaki K, Okumura T, Takahashi K (2020) Ethylene induced flower opening, expression of receptor genes, and antioxidant defensive responses in cut roses. Russ J Plant Physiol 67(4):715–723. https://doi.org/10.1134/S1021443720040081

Kim HJ, Kim SJ, An DS, Lee DS (2014) Monitoring and modelling of headspace-gas concentration changes for shelf life control of a glass packaged perishable food. LWT Food Sci Technol 55(2):685–689. https://doi.org/10.1016/j.lwt.2013.10.018

Kondo N, Murase H, Monta M, Goto T (1999) Machine vision based quality evaluation of chrysanthemum cut flower. IFAC Proc Vol 32(2):5617–5621. https://doi.org/10.1016/s1474-6670(17)56958-x

Lippmann R, Babben S, Menger A, Delker C, Quint M (2019) Development of wild and cultivated plants under global warming conditions. Curr Biol 29(24):PR1326-R1338. https://doi.org/10.1016/j.cub.2019.10.016

Ma N, Cai L, Lu W, Tan H, Gao J (2005) Exogenous ethylene influences flower opening of cut roses (*Rosa hybrida*) by regulating the genes encoding ethylene biosynthesis enzymes. Sci China Ser C Life Sci 48(5):434–444. https://doi.org/10.1360/062004-37

Macnish AJ, Jiang CZ, Reid MS (2010) Treatment with thidiazuron improves opening and vase life of iris flowers. Postharvest Biol Technol 56(1):77–84. https://doi.org/10.1016/j.postharvbio.2009.11.011

Mallahi T, Ramezanian A, Saharkhiz MJ, Javanmardi J, Iraji A (2018) Antimicrobial activities of Asafoetida and Shirazi thyme essential oils improve the vase life of gerbera cut flowers. Acta Ecol Sin 38(3):228–233. https://doi.org/10.1016/j.chnaes.2017.08.009

Mendoza R, Castellanos DA, García JC, Vargas JC, Herrera AO (2016) Ethylene production, respiration and gas exchange modelling in modified atmosphere packaging for banana fruits. Int J Food Sci Technol 51(3):777–788. https://doi.org/10.1111/ijfs.13037

Monteiro JA, Nell TA, Barrett JE (2002) Effects of exogenous sucrose on carbohydrate levels, flower respiration and longevity of potted miniature rose (*Rosa hybrida*) flowers during postproduction. Postharvest Biol Technol 26(2):221–229. https://doi.org/10.1016/S0925-5214(02)00010-8

Müller R, Andersen AS, Serek M (1998) Differences in display life of miniature potted roses (*Rosa hybrida* L.). Sci Hortic 76(1–2):59–71. https://doi.org/10.1016/S0304-4238(98)00132-0

Müller R, Sisler EC, Serek M (2000) Stress induced ethylene production, ethylene binding, and the response to the ethylene action inhibitor 1-MCP in miniature roses. Sci Hortic 83(1):51–59. https://doi.org/10.1016/S0304-4238(99)00099-0

Onozaki T, Ikeda H, Yamaguchi T (2001) Genetic improvement of vase life of carnation flowers by crossing and selection. Sci

Hortic 87(1–2):107–120. https://doi.org/10.1016/S0304-4238(00)00167-9

Park DY, Naing AH, Ai TN, Han JS, Kang IK, Kim CK (2017) Synergistic effect of nano-sliver with sucrose on extending vase life of the carnation cv. Edun. Front Plant Sci 8:1–10. https://doi.org/10.3389/fpls.2017.01601

Pouri HA, Nejad AR, Shahbazi F (2017) Effects of simulated in-transit vibration on the vase life and post-harvest characteristics of cut rose flowers. Hortic Environ Biotechnol 58(1):38–47. https://doi.org/10.1007/s13580-017-0069-5

Salaemae N, Satoh S, Imsabai W, Takeda S, Kaewsuksaeng S (2018) The combination of EthylBloc Sachet and 2,4-pyridinedicarboxylic acid reduces petal blackening and prolongs vase life of cut flowers of lotus (*Nelumbo nucifera* Gaerth) cvs. Sattabongkot and Saddhabutra. Sci Hortic 240(June):133–138. https://doi.org/10.1016/j.scienta.2018.04.066

Sane AP, Tripathi SK, Nath P (2007) Petal abscission in rose (*Rosa bourboniana* var Gruss an Teplitz) is associated with the enhanced expression of an alpha expansin gene, RbEXPA1. Plant Sci 172(3):481–487. https://doi.org/10.1016/j.plantsci.2006.10.005

Scariot V, Paradiso R, Rogers H, De Pascale S (2014) Ethylene control in cut flowers: Classical and innovative approaches. Postharvest Biol Technol 97:83–92. https://doi.org/10.1016/j.postharvbio.2014.06.010

Serek M, Woltering EJ, Sisler EC, Frello S, Sriskandarajah S (2006) Controlling ethylene responses in flowers at the receptor level. Biotechnol Adv 24(4):368–381. https://doi.org/10.1016/j.biotechadv.2006.01.007

Shahri W, Tahir I (2011) Flower senescence-strategies and some associated events. Bot Rev 77(2):152–184. https://doi.org/10.1007/s12229-011-9063-2

Sierra NM, Londoño A, Gómez JM, Herrera AO, Castellanos DA (2019) Evaluation and modeling of changes in shelf life, firmness and color of 'Hass' avocado depending on storage temperature. Food Sci Technol Int 25(5):370–384. https://doi.org/10.1177/1082013219826825

Singh P, Singh AP, Sane AP (2019) Differential and reciprocal regulation of ethylene pathway genes regulates petal abscission in fragrant and non-fragrant roses. Plant Sci 280:330–339. https://doi.org/10.1016/j.plantsci.2018.12.013

Sousa AR, Oliveira JC, Sousa-Gallagher MJ (2017) Determination of the respiration rate parameters of cherry tomatoes and their joint confidence regions using closed systems. J Food Eng 206:13–22. https://doi.org/10.1016/j.jfoodeng.2017.02.026

Tan H, Liu X, Ma N, Xue J, Lu W, Bai J, Gao J (2006) Ethylene-influenced flower opening and expression of genes encoding Etrs, Ctrs, and Ein3s in two cut rose cultivars. Postharvest Biol Technol 40(2):97–105. https://doi.org/10.1016/j.postharvbio.2006.01.007

Teixeira JA (2016) Ornamental cut flowers: physiology in practice. Floric Ornam Plant Biotechnol 1:124–140

Tromp SO, van der Sman RGM, Vollebregt HM, Woltering EJ (2012) On the prediction of the remaining vase life of cut roses. Postharvest Biol Technol 70:42–50. https://doi.org/10.1016/j.postharvbio.2012.04.003

Vehniwal SS, Abbey L (2019) Cut flower vase life—influential factors, metabolism and organic formulation. Hortic Int J 3(6):275–281. https://doi.org/10.15406/hij.2019.03.00142

Williamson VG, Rezvani F, Li G, Hepworth G (2018) An investigation of ethylene sensitivity in three Australian native cut flower genera, Calothamnus, Grevillea and Philotheca. Sci Hortic 230:149–154. https://doi.org/10.1016/j.scienta.2017.11.030

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.