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ARTICLE

Nutrient solutions and irrigation frequency using ebb and flow subsurface system for cut flower roses cultivated in greenhouse

Soluções nutritivas e frequencia de irrigação usando sistema de irrigação subsuperficial de fluxo e refluxo para cultivo de rosas em estufa

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Abstract: The ebb and flow subsurface irrigation system is presented as a technique capable of optimizing hydroponic rose production in greenhouses. We compared plant development, foliar nutrient accumulation, flower production and quality, and the occurrence of phytophagous arthropods and natural enemies in three varieties of roses subjected to three daily irrigation frequencies and three nutrient solutions. There were no significant differences due to irrigation frequency, with only one cycle every 24 hours being sufficient. Solutions 1 and 3 were able to produce flowers meeting commercial quality standards, with solution 1 - tipically used for fruit vegetables – being the most suitable overall for maintaining plant nutritional health, enhancing production, and managing populations of both undesirable and beneficial arthropods. Its formulation appears to be approached an ideal condition, yet it could still be improved regarding the concentration of some nutrients.
Keywords: Floriculture, ornamental plant, pest insects, *Rosa* sp., soilless culture.

Resumo: O sistema de irrigação subsuperficial de fluxo e refluxo é mostrado como uma técnica capaz de otimizar a produção hidropônica de rosas em estufa com cobertura plástica. Nós comparamos o desenvolvimento da planta, o acúmulo de nutrientes foliares, a produção e qualidade das flores e a ocorrência de artrópodes fitófagos e inimigos naturais em três variedades de rosas submetidas a três frequências diárias de irrigação e três soluções nutritivas. Não houve diferenças devido à frequência de irrigação e apenas um ciclo a cada 24 h foi suficiente. As soluções 1 e 3 foram capazes de proporcionar a produção de flores com padrões comerciais de qualidade. A solução 1 (usualmente usada para hortaliças frutíferas) foi a mais adequada entre todas, tanto para manter a saúde nutricional da planta e sua produção, quanto para um melhor manejo populacional de artrópodes indesejáveis e benéficos. Sua formulação parece ter se aproximado de uma condição ideal; no entanto, ainda pode ser melhorada quanto à concentração de alguns nutrientes.
Palavras-chave: Floricultura, planta ornamental, insetos-praga, *Rosa* sp., cultura sem solo.

Introduction

Roses (*Rosa* spp.) are the best-selling cut flowers globally. Their agricultural and commercial success largely stems from the ease of producing hybrids through both traditional and molecular genetic techniques. These advancements enable the development of a wide variety of colors, flower shapes, disease resistance, and improved post-harvest quality (Almeida et al., 2014; Chen et al., 2022; Gun et al., 2023; Faust and Dole, 2021).

In general, all species and varieties of roses require regular nutritional replenishment to ensure consistent harvests of floral stems that meet commercial standards. As a result, farmers often engage in excessive fertilization, overlooking the actual nutritional needs of the plants. This practice increases production costs and contributes to soil salinization. Similarly, to prevent water stress, many horticulturists apply excessive irrigation, leading to waste and elevating both financial and environmental costs (Avellar et al., 2021; Galal et al., 2022; Boldrin et al., 2022; Hamedi et al., 2022).

In addition to irrigation and fertilization, pest and disease management poses another challenge for rose growers, with chemical control often being the primary - and sometimes the only - method for reducing insect pest populations. Given these conditions, inadequate crop management can lead to physiological imbalances and metabolic disorders in the plants. Nutritional imbalances can further increase the vulnerability of plants to pest attacks (Avellar et al., 2021; Oksel et al., 2024).

On the other hand, the well-documented issues associated with pesticide use have prompted the adoption of ecologically sustainable techniques, including integrated pest management (Kumar et al., 2021). Consequently, improving fertilization and irrigation practices can help reduce production costs, enhance productivity, minimize environmental impacts, and even decrease the incidence of pests and diseases. The ebb and flow (or ebb and flood) subsurface irrigation system delivers water and nutrient solutions to plant roots through capillarity, allowing excess solution to return to a reservoir for reuse in subsequent irrigations. This technique has been widely adopted in Europe and North America, particularly in the cultivation of ornamental plants, vegetables, and fruit tree seedlings. A large number of ornamental species have been cultivated in soilless systems due to their advantages (Boldrin et al., 2022; Chandel et al., 2024).

In the ebb and flow system, plants grow without soil or with a substrate solely for support, such as coconut fiber, while nutrition is provided through fertigation. This system offers several advantages: 1) high production potential relative to minimal substrate costs; 2) recirculation of drained fractions, which prevents environmental pollution and groundwater contamination from fertilizer and pesticide leaching; and 3) reduced labor and time requirements for crop irrigation (Boldrin et al., 2022; Benko et al., 2024).

Despite the potential of the ebb and flow system for flower cultivation, its adoption among farmers remains limited, primarily due to insufficient information on the specific water and nutritional needs of each crop. Therefore, we evaluated the viability of the ebb and flow subsurface irrigation system for rose cultivation by comparing different irrigation frequencies and nutrient solutions. Our focus was on their effects on floral stem production and quality, as well as on the occurrence of phytophagous arthropods and their natural enemies.

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Materials and Methods

Description of the system and experiment setup

The experiment took place in a greenhouse (7 m x 21 m) situated at an altitude of 910 m a.s.l., latitude 21°08’08” S and longitude 44°15’42” W. The irrigation method used was an ebb and flow subsurface system, which included pots, trays on benches, and a series of plastic water tanks and motor pumps. The 11-liter plastic pots were lined with 0.02 m of type 3222-grade expanded clay and then filled with a mixture of coconut fiber substrate. The fiber was prehydrated for 24-h. Next, rose seedlings that were 0.5 m tall and produced through grafting had their roots cleaned to remove any adhered soil. Following the cleaning, two seedlings were planted in each pot, which were placed inside plastic trays measuring 0.7 m in length, 0.5 m in width, and 0.22 m in height, with two pots per tray (Fig. 1).

Fig. 1. Details of the ebb and flow subsurface irrigation system used in the experiments.

Part of the fertigation mechanism was installed on the outside of the greenhouse, consisting of 500 L covered water tanks connected by polyvinyl chloride (PVC) pipes to the interior of the greenhouse. The hydraulic circuit was composed of six sets of reservoirs (water tank), motor pump and timer. Each set moved one of two different nutrient solutions (dissolved in the reservoir) at three different activation times (frequencies) for the first experiment or three different rose cultivars for the second experiment, according to six experimental treatments (2 x 3 factors).

The fertigation process involved immersing 40% - 50% of the pots from their base into the trays. The circuits were activated automatically for 15 min, during which the nutrient solutions traveled through the piping from the reservoirs to the trays with the pots inside. After 15 min, the pump was turned off by the timer, and the entire solution in the tray was returned to its respective reservoir by gravity through a drainage pipe installed on the lower side of the tray.

The different nutrient solutions were prepared using the following water-soluble fertilizers at different concentrations: monopotassium phosphate, magnesium nitrate, potassium chloride, calcium nitrate, potassium nitrate, magnesium sulfate, potassium sulfate, iron EDTA 6%, zinc sulfate, manganese sulfate, boric acid, copper sulfate and sodium molybdate. The nutrient solutions were controlled using a portable digital conductivity meter. The pH was maintained between 5.2 and 6.0 and the electrical conductivity ranged from 1.5 and 2.5 mS^{-1}cm. Periodically, cultural care was carried out on the plants, which included pruning (removing unwanted shoots from the floral stem), placing protective nets over the flower buds, cleaning pruning, and bending of branches (agobio technique).

Irrigation frequencies and nutrient solutions on the performance of rose ‘Carola’ and associated arthropods

This experiment was designed in randomized blocks, with four replications and two causal factors to the type of nutrient solution and the temporal frequency of irrigation. We compared the effects of two nutrient solutions commonly used in hydroponic crops – one recommended for fruit vegetables and the other for leaf vegetables (Furlani et al., 1999) (Table 1). We employed three irrigation frequencies for each nutrient solution, one (24 h), two (12 h – 12 h) and three times (8 h - 8 h - 8 h) a day. Thus, the experiment had 24 plots, consisting of six bifactorial treatments with four replicates each. The experimental unit (replicate) was two trays containing two pots each, with each pot having two plants (eight plants per sample plot).

Table 1. Nutrient solutions (mg L^{-1}) used in the ebb and flow subsurface system for cut flower roses cultivated in greenhouse.

Nutrient	Solution 1 for fruit vegetables (Furlani et al., 1999)	Solution 2 for leaf vegetables (Furlani et al., 1999)	Solution 3 (Ehret et al., 2005)
N-NO_3^-	169	238	424.7*
P	62	62	152
K	311	426	265.2
Ca	153	161	150
Mg	43	24	21.6
S	50	32	76.8
B	0.2	0.3	0.51
Cu	0.03	0.05	0.13
Fe	4.3	5.0	2.02
Mn	1.1	0.4	0.39
Mo	0.05	0.05	0.06
Zn	0.3	0.3	0.26

50% of the dose recommended by Ehret et al., 2005

Biometric traits of floral stems of rose 'Carola' (*Rosa* sp.) were measured, harvested three times a week for twelve months, starting from the growth of the seedlings and the beginning of the plant's flowering. The flowers were harvested and quantified when they reached commercial standards, at the medium opening stage (Almeida et al., 2014). The following variables were measured: number of stems produced per plant, number of leaves per stem, length and diameter of the stem, length and diameter of the floral bud and biomass of stems, leaves and floral buds.

A chemical analysis of macro and micronutrient content of the leaves was carried out after 12 months of cultivation to compare the accumulation and concentration of nutrients. For this, the third leaf of the aerial part, with five leaflets, was collected - five leaves per experimental plot.

Finally, the density of phytophagous arthropods and natural enemies (predators and parasitoids) on plants were measured weekly during six months. The number of individuals present on one of the two plants in each pot (sample plot was two trays containing two pots each) was quantified, considering only three leaves per plant, chosen randomly from the upper, middle and lower strata. Threfore, twelve leaves in four plants per sample plot were visually inspected every week. Common and known species were counted without removal. Only unknown specimens were collected with a mouth sucker or fine-tipped brush and stored in 70% alcohol for later identification in laboratory. Identification was made with the aid of taxonomic keys. At the end of the sampling period, the average number of individuals per leaf per plant was calculated.

All plants were equally sprayed, when necessary, with the following products: neem oil (*Azadirachta indica* A. Juss) Nim-I-Go® (0.1%), for the prevention and control of aphids (Aphididae), and sodium bicarbonate (1%) for powdery mildew. For the prevention and control of mites, spraying was carried out with a strong jet of water whenever the first individuals appeared. After the arthropod sampling period, 11 sprays of chemical pesticides registered for rose cultivation were applied to control powdery mildew, mildew (Fungi), aphids (Aphididae) and mites (Acari). All plants were sprayed every two weeks with the foliar fertilizers Biofert® (10 mL L^{-1}), Sulfur (2 mL L^{-1}), Bion® (0.05g L^{-1}) and Greenforce® (10 mL L^{-1}).

Nutrient solutions and rose cultivars on plant performance

This experiment was also designed in randomized blocks, with four replications and two causal factors corresponding to the type of nutrient solution and the cultivar of rose. We compared the effects of two nutrient solutions: the one that showed the best result in the previous test (nutrient solution 1) and a nutrient solution based on Ehret et al. (2005) (nutrient solution 3) (Table 1). The rose cultivars tested were 'Carola' red, 'Greta' pink and 'Tineke' White (*Rosa* sp.). Thus, the experiment had 24 plots, consisting of six bifactorial treatments with four replicates each. The experimental unit was two trays containing two pots each, each pot having two plants (eight plants per sample plot).

Biometric traits of floral stems were measured, harvested three times a week for ten months, starting from the growth of the seedlings and the beginning of the plant's flowering. The flowers were harvested and quantified when they reached commercial standards, at the medium opening stage (Almeida et al., 2014). The following variables were measured: number of stems produced per plant, number of leaves per stem, length and diameter of the stem, length and diameter of the floral bud, and biomass of stems, leaves and floral buds.

Statistical analysis

The bionomic traits of the plants and the arthropod densities were calculated as general averages per plant per sample plot. Data normality was verified using the Kolmogorov–Smirnov test, and homogeneity of variances was assessed by Bartlett's test. After passing these tests, the data were subjected to two-way analysis of variance (two-way ANOVA) as a function of nutrient solution and irrigation frequency or rose cultivar. After finding a non-significant influence of irrigation frequency on any response variable, means were compared using Student's t-test as a function of nutrient solution alone. In the second experiment, after two-way ANOVA, means were compared using the Holm-Sidak HSD test at 5%. All analyzes were performed using the SigmaPlot 14.5 statistical package, Systat Software Inc., San Jose, CA, USA.

Results

Bionomy, flower production, and leaf nutrients of rose 'Carola' under different irrigation frequencies and nutrient solutions

Two-factor analysis of variance showed that irrigation frequency and interaction between frequency and nutrient solution did not significantly affect ($p > 0.05$, total DF = 23) any of the following bionomic traits and production of floral stems of rose 'Carola': flower stem length, flower bud length, flower stem diameter, flower bud diameter, number of leaves, fresh weight of flower stem, dry weight of flower stem, fresh weight of leaves, dry weight of leaves, fresh weight of flower bud, dry weight of flower bud and number of flower stems per plant). However, two-way ANOVA indicated that nutrient solutions affected rose bionomic traits ($p < 0.01$ or less, with DF = 23), except for flower stem length ($p > 0.05$). Then, data were compared again using Student's t-test as a function of nutrient solution alone (Table 2). In both nutrient solutions, the plants produced floral stems of commercial quality standard, according to Almeida et al. (2014), and did not show symptoms of nutritional deficiency (Table 2).

Table 2. Comparison of bionomic traits and flower production (mean ± SD) by rose 'Carola' due to the effect of the type of nutrient solution in an ebb and flow subsurface flood irrigation system.

RESPONSE VARIABLE	NUTRIENT SOLUTION	
	1	2
Flower stem length (cm) *ns*	66.0 ± 2.7	63.9 ± 5.4
Flower bud length (mm) ***	51.3 ± 1.2	49.1 ± 1.5
Flower stem diameter (mm) *	6.0 ± 0.3	5.6 ± 0.4
Flower bud diameter (mm) *	36.6 ± 0.7	35.1 ± 1.4
Number of leaves (per stem) ***	12.5 ± 0.9	10.9 ± 1.0
Fresh weight of flower stem (g) ***	13.2 ± 1.7	10.3 ± 1.4
Dry weight of flower stem (g) ***	3.9 ± 0.4	3.0 ± 0.4
Fresh weight of leaves (g) ***	14.6 ± 1.1	12.2 ± 1.1
Dry weight of leaves (g) *	4.2 ± 1.1	3.3 ± 0.3
Fresh weight of flower bud (g) ***	13.5 ± 0.7	12.1 ± 0.8
Dry weight of flower bud (g) ***	2.1 ± 0.1	1.9 ± 0.2
Number of flower stems (plant/year) ***	16.1 ± 1.9	6.3 ± 1.7

ns $p > 0.05$; * $p < 0.01$; ** $p < 0.001$ and *** $p < 0.0001$ between means by Student's t-test.

The diameter of the floral stems was greater than the minimum required of 5.0 mm. The stem length can be classified as either class 70 or class 60 - 70, in both nutritional conditions. On the other hand, nutrient solution 1 (for fruit vegetables) provided better quality flower stems (higher measurement values), compared to nutrient solution 2 (for leafy vegetables), which produced flower buds classified as small to medium (Almeida et al., 2014). Additionally, over the course of a year, rose bushes treated with nutrient solution 1 produced about 60% more flower stems per plant (Table 2).

Two-factor analysis of variance showed that irrigation frequency affected leaf concentrations of N, P, Ca, Mg, and S, and the interaction between frequency and nutrient solution significantly effected P, Mg, B, Cu, and Zn ($p < 0.01$, total DF = 23). However, frequency and interaction of factors were not important in determining production and plant bionomy. Nutrient solution affected leaf concentrations of P, Ca, Mg, Mn, Zn, and Fe ($p < 0.0001$); threrefore, nutrient solution 1 resulted in significantly higher leaf concentrations of Mg, Mn, Zn, and Fe, although it was less efficient than nutrient solution 2 for P and Ca (Table 3).

Table 3. Comparison of nutrient concentration (mean ± SD) in leaves of rose 'Carola' due to the effect of the type of nutrient solution, in an ebb and flow subsurface flood irrigation system.

Nutrient in leaves	Nutrient solution*	
	1	2
Phosphor (%)	0.54 ± 0.05	0.60 ± 0.06
Calcium (%)	1.16 ± 0.12	1.33 ± 0.12
Magnesium (%)	0.23 ± 0.01	0.18 ± 0.02
Manganese (ppm)	17.3 ± 3.68	0.5 ± 0.35
Zinc (ppm)	21.7 ± 4.14	15.7 ± 2.72
Iron (ppm)	156.1 ± 10.01	129.67 ± 4.03

* $p < 0.0001$ between means by the Student's t-test for all nutrients

After one-year, nutrient solution 1 allowed for greater accumulation of nutrients in the leaves for all nutrientes (Table 4). The nutrients S, Mg and Mn were used in greater quantities in nutrient solution 1 (50, 43, and 1.1 mg L^{-1}, respectively) compared to nutrient solution 2 (32, 24, and 0.4 mg L^{-1}, respectively), and were also more accumulated in plants that received solution 1. Conversely, N, K, B, Ca, Fe, and Cu were used in higher concentrations in nutrient solution 2 (238, 426, 0.3, 161, 5.0, and 0.05 mg L^{-1}, respectively) compared to solution 1 (169, 311, 0.2, 153, 4.3, and 0.03 mgL^{-1}, respectively). Despite this, these elements accumulated more in leaves of plants treated with nutrient solution 1. Both solutions were formulated with the same concentrations of P and Zn (62 and 0.3 mg L^{-1}, respectively), however, they were accumulated more effectively in plants treated with solution 1.

Table 4. Comparison of nutrient concentration (mean ± SD) in leaves of rose 'Carola' due to the effect of the type of nutrient solution, in an ebb and flow subsurface flood irrigation system.

Nutrient in leaves (mg kg^{-1})#	Nutrient solution*	
	1	2
Nitrogen	133.7 ± 1.62	108.6 ± 2.03
Phosphor	22.6 ± 0.66	19.9 ± 0.61
Potassium	106.1 ± 1.77	84.2 ± 1.63
Calcium	48.6 ± 1.39	44.0 ± 1.13
Magnesium	9.7 ± 0.13	5.9 ± 0.14
Sulfur	13.6 ± 0.38	11.1 ± 0.25
Boron	0.42 ± 0.014	0.37 ± 0.022
Copper	0.025 ± 0.0017	0.018 ± 0.0015
Manganese	0.073 ± 0.0155	0.0017 ± 0.00116
Zinc	0.091 ± 0.0050	0.052 ± 0.0026
Iron	0.66 ± 0.042	0.43 ± 0.013

\# mg kg^{-1} = concentration (g kg^{-1}) x leaf dry mass (g $plant^{-1}$)/1000g.

* $p < 0.0001$ between means by Student's t-test for all nutrients.

Arthropods associated with rose 'Carola' under different irrigation frequencies and nutrient solutions

The insects and mites associated with the rose bushes in all treatments can be divided into two categories based on their predominant food habits. The phytophagous groups included: mites *Tetranychus urticae* (Acari: Tetranychidae), aphids *Macrosiphum rosae*, *Macrosiphum euphorbiae* and *Rhodobium porosum* (Hemiptera: Aphididae), whiteflies *Bemisia tabaci* (Hemiptera: Aleyrodidae), thrips *Frankliniella occidentalis* and *Frankliniella schultzei* (Thysanoptera: Thripidae) and coleoptera *Diabrotica speciosa* (Coleoptera: Chrysomelidae). Also sporadically sampled and unidentified were Cicadellidae and Membracidae (Hemiptera), Acrididae (Orthoptera) and Lepidoptera larvae. The main parasitoid was *Praon volucre* (Hymenoptera: Braconidae) and the predators were *Chrysoperla externa* (Neuroptera: Chrysopidae), *Cycloneda sanguinea* and *Hippodamia convergens* (Coleoptera: Coccinellidae), *Toxomerus* sp. (Diptera: Syrphidae), as well as the mite *Neoseiulus californicus* and various spiders (Araneae).

Two-factor analysis of variance showed that irrigation frequency and interaction between frequency and nutrient solution did not significantly affect ($p > 0.2$, total DF = 23) the density of following groups of arthopods on leaves of rose 'Carola': Aphididae, *N. californicus*, *T. urticae*, Thripidae, Syrphidae, Coccinelidae, Aphididae mummies. The type of nutrient solution affected the number of aphids (Aphididae) ($p = 0.001$) and the predator mite *Neoseiulus californicus* ($p = 0.002$), although it did not influence other groups ($p > 0.05$). The phytophagous aphids were numerically less abundant in solution 1 compared to solution 2, while the predator mite benefited from solution 1 (Fig. 2).

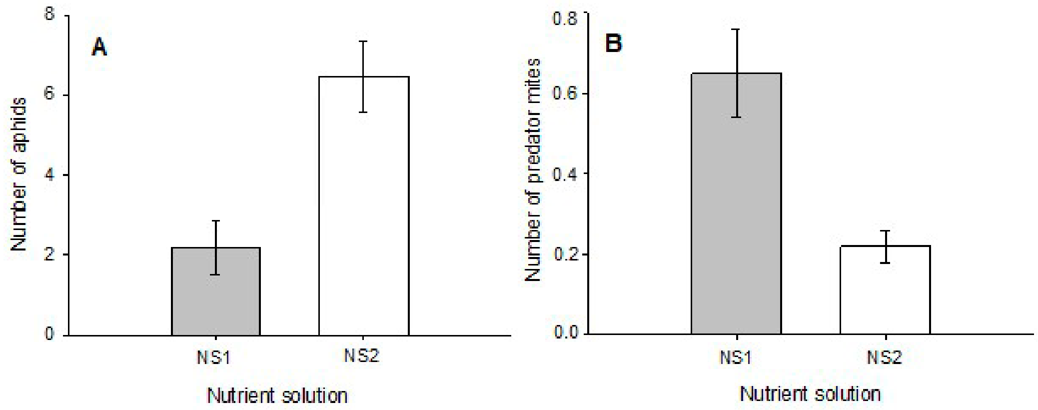

Fig 2. Densities (individuals per plot) of Aphididae (A) and predator mite *Neoseiulus californicus* (B) on leaves of rose 'Carola' due to the type of nutrient solution in an ebb and flow subsurface flood irrigation system. Significant differences ($p < 0.001$) for both, as determined by the Student's t test, with bars and lines showing means ± SD.

Nutrient solutions and rose cultivars on plant bionomy and flower production

Two-factor analysis of variance showed that, except for flower stem length ($p = 0.02$) and dry weight of flower bud ($p = 0.005$), nutrient solution did not significantly affect the following plant traits ($p > 0.05$, total DF = 40): flower bud length, flower stem diameter, flower bud diameter, number of leaves, fresh weight of flower stem, and dry weight of flower stem, fresh weight of leaves, dry weight of leaves, fresh weight of flower bud, and total number of flower stems per plant. The interaction between nutrient solution and rose cultivar did not affect any bionomic trait or flower production ($p > 0.05$); therefore, the effects of nutrient solution did not differ from one cultivar to another. However, the type of cultivar determined significant diferences ($p < 0.05$, total DF = 40) in most bionomic traits, such as: flower stem length, flower bud diameter, number of leaves, fresh weight of flower stem, and dry weight of flower stem, fresh weight of leaves, fresh weight of flower bud, and total number of flower stems per plant. The type of cultivar did not affect ($p > 0.05$) flower bud length, flower stem diameter, dry weight of leaves, and dry weight of flower bud.

In all rose cultivars, the characteristics of the flower stems, whether produced in nutrient solution 1 or nutrient solution 3, generally met the quality standards required for cut roses, according to Almeida et al. (2014) (Figs. 3 and 4). The stem length met the commercial standard in 'Carola' in both nutrient solutions and can be classified as class 60 (Almeida et al., 2014). The type of solution also did not affect stem length in 'Tineke'; however, nutrient solution 3 exceptionally stimulated longer stems in 'Greta' (Fig. 3). Despite this, 'Greta' showed a tendency towards lower measurements in other traits (Fig 4). Cultivars 'Carola' and 'Tineke' exhibited larger flower bud diameters (Fig. 4A), but 'Carola' stood out in terms of fresh and dry stem biomass (Fig. 4 B-C), as well as in the number and fresh biomass of steam leaves (Fig. 4 D-E). Conversely, 'Tineke' showed the highest productivity in the number of stems per plant (Fig. 4F)

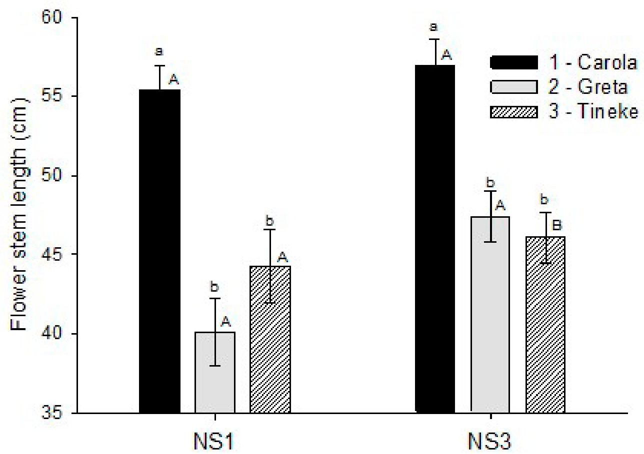

Fig 3. Effect of nutrient solutions (NS1 and NS3) on the length of flower stems of rose cultivars ('Carola', 'Greta', and 'Tineke') grown in an ebb and flow subsurface flood irrigation system. Different lowercase letters indicate different responses among rose cultivars in the same nutrient solution, while different uppercase letters indicate significant differences due to nutrient solutions in the same cultivar, according to the Holm-Sidak post hoc test ($p > 0.05$).

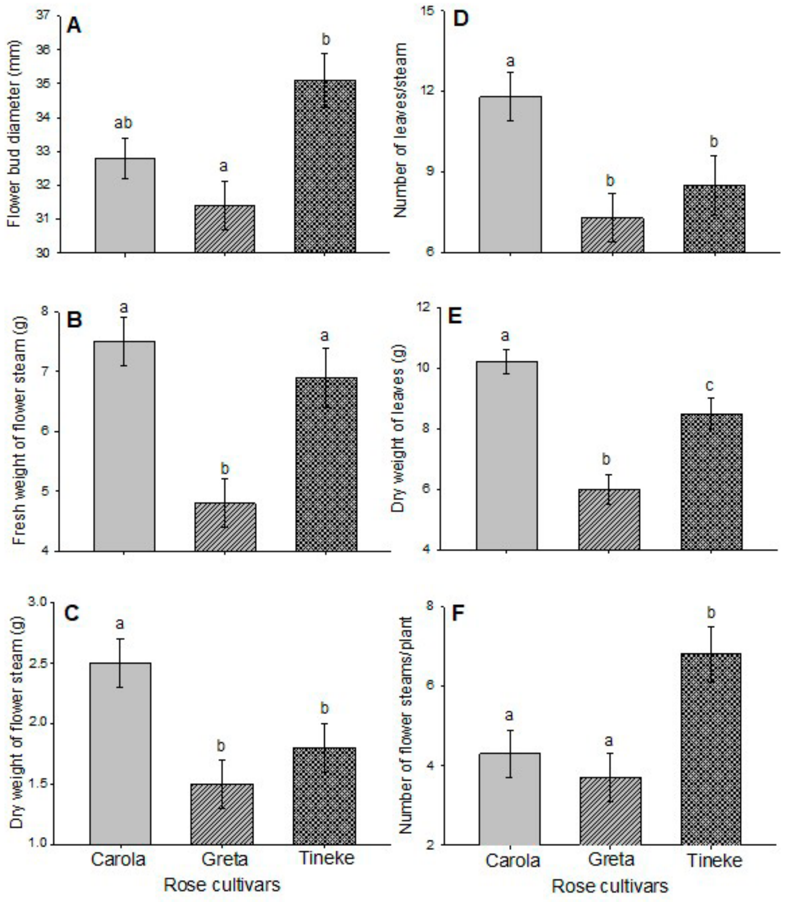

Fig 4. Bionomics (A-E) and floral productivity (F) of rose cultivars (‘Carola’, ‘Greta’ and ‘Tineke’) grown in an ebb and flow subsurface flood irrigation system. Different letters between columns of the same chart indicate significant differences between cultivars by the Holm-Sidak post hoc test ($p > 0.05$). The interactions between nutrient solutions and rose cultivars were not significant ($p > 0.05$) by ANOVA.

Discussion

An important requirement for successful plant soilless production is to adjust the daily rhythm of water and nutrient supply. Under the ebb and flow conditions of this study, we demonstrated that one irrigation every 24-h was sufficient, with shorter intervals being unnecessary and costly. In our experiment, the low frequency of irrigation may have been favored by the type of support substrate used. The mixed coconut fiber comprises micropores that allow for nutrient retention and rapid drainage of the solution, ensuring adequate aeration and oxygenation of the substrate and roots. According to Fascella and Zizzo (2005), coconut fiber offers a high capacity for water retention and cation exchange, proving to be highly effective for growing rose cultivars such as Anastasia, Fenice, New fashion and Gold strike in an open hydroponic system.

For soilless plant cultivation, the correct formulation of nutrient solutions is crucial. This study presented, for the first time, a comparative analysis of the efficiency of three nutrient formulations for growing roses in ebb and flow subsurface irrigation systems. Although all formulations were suitable for producing flowers that met market quality standards, nutrient solutions 1 (typically indicated for fruit vegetables) and 3, based on Ehret et al. (2005) demonstrated similar effects and were more suitable compared to nutrient solution 2 (usually indicated for leafy vegetables). Nutrient solution 1 enabled a level of production and quality of roses that aligns with previous results for both soilless cultivation and other systems (Avellar et al., 2021; Boldrin et al., 2022).

Stem length is one important characteristic for evaluating the quality of cut roses and it is the main indicator of their economic value. In this study, the ‘Carola’ flower stems reached the quality standards required for cut roses, showing a length greater than 50 cm in all nutrient solutions, although they were longer in solutions 1 and 3. The ‘Carola’ stems, despite not having reached the highest classification, are among the best commercially rated classes. On the other hand, ‘Greta’ and ‘Tineke’ reached lower average stem lengths of around 40 to 45 cm, falling into classes 40 and 50, respectively (Almeida et al., 2014). For example, flower stem length ranged from 20.78 to 50.95 cm in *Rosa hybrida* L. cv. Red Velvet in closed hydroponic system (Yeo et al., 2016), from 58.4 to 63.8 cm in *Rosa kardinal* in soilless culture (Ehret et al., 2005), from 58.1 to 65 cm in *Rosa* cv. Anastasia, Fenice, New Fashion and Gold Strike in an open hydroponic system (Fascella and Zizzo, 2005). Therefore, stem lengths found here for the ebb and flow system were compatible with measurements in other cultivars and growing conditions. Regarding the stem length, nutrient solutions 1 and 3 could be better indicated for use in ebb and flow systems.

In addition to stem length, flower bud quality is essential from a commercial standpoint. The ‘Carola’ rose cultivated with nutrient solution 1 showed a bud length of 51.3 mm, classified as medium, since the minimum required is 50.0 mm (Almeida et al., 2014). For all rose varieties, bud diameters (36.6 mm) were also greater in nutrient solutions 1 and 3 compared to solution 2. Despite differences among cultivars, the bud measurements in the ebb and flow system were compatible with those from other production systems. For example, cultivars Anastasia, Fenice, New Fashion, and Gold Strike in open hydroponic systems had bud lengths ranging from 51 to 58 mm and diameters from 50 to 53 mm (Fascella and Zizzo, 2005).

In the first experiment, both fresh and dry biomass of stems, leaves, and buds were greater in nutrient solution 1 compared to solution 2. In the second experiment, the dry weight of buds was higher in solution 1 than in solution 3, despite the latter containing 60% more nitrogen. According to Bafoev et al. (2022), dry biomass consists of less than 10% inorganic elements essential to plant metabolism, while the remaining 90% comprises compounds derived from photosynthesis, serving structural, metabolic, or reserve functions. Thus, the dry biomass of plant organs can be used as an indirect measure of productivity and development, reflecting the plant's nutritional status. Therefore, based on dry weight and floral bud quality, nutrient solutions 1 and 3 could be better suited for ebb and flow systems in the commercial production of roses.

The optimal ratio of macro and micronutrients varies with plant species, and their effects also depend on growing conditions and substrate (Manimaran et al., 2017). Correct nutrient proportions are essential, as excessive amounts of some can reduce the absorption of others, leading to toxic effects that negatively impact rose growth and production (Yeo et al., 2016). The nutrient ratios in solution 2 may have been inadequate, as it performed worse than the others. Plant growth directly depends on the root's capacity to absorb water and nutrients (Kwon and Choi, 2022), underscoring the importance of substrate type. In this study, the quality and production of flower stems and buds indicated that nutrient solutions 1 and 3 may approach an ideal formulation for use with coconut fiber substrate in ebb and flow systems, particularly for the 'Carola'. In the second experiment, solutions 1 and 3 showed similar effects across all cultivars; however, 'Carola' demonstrated better developmental and qualitative characteristics from a commercial perspective, despite lower quantitative performance compared to 'Tineke'.

The usual production of roses with high nitrogen concentrations in irrigation water (150 - 200 mg L^{-1} N) may lead to nutrient leaching (Yeo et al., 2016). General symptoms of nitrogen deficiency - such as stunted growth, shorter internodes, and pale-yellow leaves (Yeo et al., 2016) - were not observed in this study, which recorded nitrogen nitrate ($N\text{-}NO_3^-$) concentrations of 169 mg L^{-1}, 238 mg L^{-1}, and 424.7 mg L^{-1} for nutrient solutions 1, 2, and 3, respectively. Reducing the recommended nitrogen concentration from 100 mg L^{-1} to 75 mg L^{-1} did not negatively impact productivity or quality in *Rosa hybrida* cv. Tropicana under soilless cultivation (Chow et al., 2009). Therefore, solution 1 was more suitable due to its better or equivalent efficiency with a lower nitrogen concentration. The highest concentration in solution 3 did not enhance the production or quality of flower stems and buds. Beyond plant bionomic traits, the nutrient levels accumulated in leaves further support the suitability of nutrient solution 1, as it resulted in greater accumulation of all nutrients compared to plants treated with nutrient solution 2. In the second experiment, no differences regarding the type of nutrient solution were observed, again reinforcing the recommendation of nutrient solution 1 for growing roses in ebb and flow subsurface flood irrigation systems, especially for the 'Carola'.

Nutrient accumulation in plants helps determine appropriate fertilizer application rates. The 'Carola' treated with solutions 1 and 2 exhibited excessive phosphorus concentrations, while zinc concentrations were adequate, and foliar concentrations of nitrogen and copper were low in both experiments, according to Vetanovetz (1996). Yeo et al. (2016) identified ideal concentrations for red velvet roses in a closed hydroponic system as 100 - 150 mg L^{-1} N, 30 - 50 mg L^{-1} P, and 100 - 150 mg L^{-1} K, considering nutrient absorption and overall plant growth. While foliar potassium concentrations were ideal in both experiments, boron concentrations were high. Magnesium and manganese absorption did not meet the plants' nutritional demands, leading to diagnosed foliar deficiencies in both solutions 1 and 2, with values below 2.5 g L^{-1} for magnesium and 30 mg L^{-1} for manganese. Despite this, it cannot be concluded that severe manganese deficiency caused lower stem production. Foliar calcium concentrations were adequate for roses, while iron concentrations were high in solution 2 and excessive in solution 1. Although solution 1 facilitated floral production in line with commercial standards and outperformed solution 2, leaf analyses indicated that its formulation could still be improved.

Finally, our study indicated that the type of nutrient solution can influence the occurrence of arthropods on plants, including both undesirable and beneficial species. Depending on irrigation frequency, the amount of water used, and the irrigation system type, there may be physical removal of immature or adult insects from the leaf surface (Thakur et al., 2021). Water regime can induce structural, physiological, and biochemical changes in plants, leading to varying impacts on herbivorous arthropods (Manimaran et al., 2017). In this study, the irrigation method did not physically remove arthropods from stems and leaves, and no irrigation frequency caused water stress in the plants, as differences did not affect flower production. Therefore, it is unlikely that irrigation frequency differences were significant enough to influence plant defense mechanisms against arthropods. However, the type of nutrient solution impacted various structural and physiological characteristics of the plants, which likely affected their quality as food for herbivorous arthropods, with consequences for their population densities. In fact, it is known that increased nitrogen fertilization, in particular, usually benefits biological and population traits of aphids (Aqueel and Leather, 2011; Braham et al., 2023).

Host plant quality, determined by nutritional and defense compounds, affects the choice, feeding capacity, development, and populations of herbivores (Manimaran et al., 2017). Any qualitative variations in the rose bushes resulting from the type of nutrient solution were not intense enough to affect most arthropods at the population level, although they did influence the abundance of aphids and predatory mites. Aphids, such as *M. rosae*, *M. euphorbiae*, and *R. porosum*, were approximately three times more abundant in 'Carola' roses subjected to nutrient solution 2, despite no differences in their typical predators, such as Syrphidae and Coccinellidae. The number of aphids attacked by the parasitoid *P. volucre* (aphid mummies) also showed no differences between treatments. This study does not delineate the relative roles of natural enemies (top-down effect) and plant nutritional characteristics (bottom-up effect) on aphid populations. Nonetheless, nutrient solution 2 seemed to favor herbivores, whereas solution 1 offered more physiological benefits to the plants, evidenced by their superior performance and production. The better nutritional state may have translated to improved protection against herbivores. In fact, nutrient solutions may influence individual and population dynamics of aphids on roses (Avellar et al., 2021).

Under different conditions, fertilization of ornamental plants may have no effect or promote the abundance of the phytophagous mite *T. urticae* (Chow et al., 2009). In this study, the abundance of *T. urticae* did not vary between plants treated with different nutrient solutions. This finding has practical importance, as nutrient solution 1, which enhanced plant performance, did not promote this common herbivore of roses. Conversely, the predatory mite *N. californicus* benefitted from this plant condition. *N. californicus* can effectively control *T. urticae* populations over extended periods (Marafeli et al., 2014), and a relationship between predator increase and herbivore decline in greenhouses has been observed (Souza-Pimentel et al., 2014). While this study does not establish a causal relationship between these species, the greater presence of the predatory mite in plants treated with nutrient solution 1, which exhibited better phytotechnical performance and a lower incidence of herbivorous mites, is of practical relevance. Notably, during the entire arthropod monitoring period, no acaricide applications were necessary to control *T. urticae*. According to Chow et al. (2009), combining bottom-up effects (manipulating fertilization) with top-down effects (via natural enemies or chemical control) could provide better *T. urticae* control than using these strategies in isolation.

Conclusion

This study demonstrated that the ebb and flow subsurface irrigation system is effective for hydroponic cultivation of roses, particularly the 'Carola', with just one irrigation cycle every 24 hours being sufficient. Among the three nutrient solutions compared, solutions 1 and 3 produced flowers that met commercial quality standards, with solution 1 being the most suitable overall for maintaining plant nutritional health, enhancing production, and managing populations of both undesirable and beneficial arthropods. Its formulation appears to approach an ideal condition, yet it could still be improved regarding the concentration of some nutrients.

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Author Contribution

WGC: Conceptualization, Supervision, Data Curation, Formal Analysis, Writing – Review & Editing. **EFAA:** Conceptualization, Supervision, Project Administration, Writing – Review & Editing. **ICSC:** Investigation, Methodology, Data Curation, Writing – Original Draft. **LMC:** Conceptualization, Supervision, Project Administration, Writing – Review & Editing. **GSA:** Investigation, Methodology, Data Curation and Writing.

Conflict of Interest

The authors declare no conflict of interests.

Data Availability Statement

Data will be made available upon request to the authors.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors declare that the use of AI and AI-assisted technologies was not applied in the writing process.

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