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Scientific Note

Yield components of *Eryngium foetidum* L. seeds as a function of capitula order[1]

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ABSTRACT

Eryngium foetidum L. seeds are still predominantly produced by family farmers, in gardens or small plots, using simple cultivation techniques. The seeds exhibit low germination rates and vigor and are acquired through exchange between local producers or from remnants in the cultivation area itself. This study aimed to identify the yield components that contribute most to the seed production of Amazon chicory. A randomized block experiment was conducted with four treatments consisting of different capitula orders (first, second and third order, and a mixture of capitula up to the fourth order) and six replicates. The following traits were assessed: days to the beginning of the foliar differentiation and to flowering, number of leaves in the vegetative, reproductive and harvest stage, number of tillers per plant, number of flowering stems per plant, number of seeds, 100-seed weight, seed production and yield. The data were submitted to correlation network analysis. The number of tillers per plant, flowering stems per plant, number of leaves at harvest and number of seeds are the components that contribute most to the *E. foetidum* seed yield.

KEYWORDS: Amazon chicory, non-conventional food plant, Apiaceae.

RESUMO

Componentes de produção de sementes de *Eryngium foetidum* L. em função da ordem dos capítulos

A produção de sementes de *Eryngium foetidum* L. ainda é predominantemente realizada pela agricultura familiar, em hortas ou quintais, sem grandes técnicas de cultivo, com sementes de baixa taxa germinativa e vigor, adquiridas por meio de troca entre produtores locais ou remanescentes da própria área de cultivo. Objetivou-se identificar os componentes de produtividade que mais contribuem para a produção de sementes de chicória da Amazônia. Foi conduzido um experimento em blocos ao acaso, com quatro tratamentos que consistiram em diferentes ordens de capítulos (primeira, segunda e terceira ordem e mistura das ordens dos capítulos, até a quarta ordem) e seis repetições. As características avaliadas foram: dias para o início da diferenciação foliar e do florescimento, número de folhas na fase vegetativa, reprodutiva e na colheita, número de perfilhos por planta, número de pendões florais por planta, número de sementes, massa de 100 sementes, produção e produtividade de sementes. Os dados foram submetidos à análise de rede de correlações. O número de perfilhos por planta, pendões florais por planta, folhas na colheita e número de sementes são os componentes que mais contribuem para a produtividade de sementes de *E. foetidum.*

PALAVRAS-CHAVE: Chicória da Amazônia, planta alimentícia não convencional, Apiaceae.

Amazon chicory (*Eryngium foetidum* L.) is a non-conventional vegetable belonging to the Apiaceae family, indigenous to tropical America and the west Indies (Paul et al. 2011). In the Amazon region, it is widely consumed as a culinary herb, particularly in regional dishes. However, there is significant interest in its medicinal properties due to the presence of bioactive compounds, primarily trans-2-dodecenal, commonly known as eryngial (Rodrigues et al. 2022).

Amazon chicory is a perennial plant with an indeterminate flowering stalk that produces capitula during the reproductive stage. Its inflorescences are capitulum-shaped, and its fruits/seeds are indehiscent diachenes (Singh et al. 2014, Lucas & Cardozo 2020, Cardozo et al. 2021). During the reproductive phase, the plant develops capitula of various maturation stages, simultaneously exhibiting mature and green primary and secondary capitula, respectively, characteristic of umbelliferous plants (Carrubba & Lombardo 2020).

In Brazil, two culantro cultivars are currently found (Brasil 2024); however, little is known about their reproductive behavior or seed production

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patterns, and research aimed at seed production indicators remains incipient.

The collection patterns of local farmers typically involve mixing seeds from all inflorescence orders to achieve the necessary amount for sowing. Harvesting occurs when the capitula change color from green to brown. However, this may compromise seed maturation and, consequently, its physiological quality, which corresponds to the optimal harvest stage, when seeds exhibit maximum germination and vigor, combined with peak dry matter accumulation and reduced water content (Marcos Filho 2015). Additionally, for indeterminate growth species such as the Amazon chicory, seed maturation varies with the capitula position on the plant (Ekpong & Sukprakarn 2006, Moraes et al. 2021).

According to Fageria et al. (2006), seed production is influenced by genetic interactions intrinsic to the species, environmental conditions and cultivation techniques. For *E. foetidum*, Mozumder et al. (2013) reported that spacing affects seed growth and yield, with wider spacings resulting in smaller plants, with a higher number of flowering stems. Thus, understanding these interactions requires an assessment of seed yield components, which, as Nakagawa (2014) describes, are typically analyzed individually or collectively at the end of the cultivation cycle.

Given the socioeconomic potential of non-conventional plants such as *E. foetidum* for biodiversity conservation and food security, coupled with the need to understand the traits influencing seed production dynamics, this study aimed to identify the yield components that contribute most to the seed production of Amazon chicory.

The experiment was conducted at the Universidade Federal Rural da Amazônia (UFRA), in Capanema, Pará state, Brazil, during the "Amazon winter" (from January to July 2023). The region's climate is classified as Am, according to the Köppen-Geiger system, with average temperature of 26 ºC and annual rainfall of 1,750-2,500 mm (Alvares et al. 2013). Daily climatic data during the experimental period were obtained from the weather station of the National Institute of Meteorology (Brasil 2023).

An experimental randomized block design was used, with four treatments and six replicates. The treatments consisted of capitula orders (first, second and third order, and a mixture of capitula up to the fourth order). Each experimental plot contained 20 plants, with only six central plants considered as the study area.

For the crop establishment, seedlings were grown from seeds obtained from the Amazon chicory seed collection at the UFRA. Sowing was performed in expanded 128-cell polystyrene trays filled with Carolina Soil® commercial substrate, containing two seeds per cell. After sowing, the trays were maintained in a protected environment and watered daily up to the field capacity. Thinning was conducted after emergence, leaving only one seedling per cell.

At 69 days after sowing, seedlings with four fully developed true leaves were transplanted to 7-m-long and 1-m-wide beds with spacing of 0.20 × 0.20 m.

Cultivation occurred in medium-textured Dystrophic Yellow Latosol (Embrapa 2018) or Ferralsol (FAO 2022). The soil analysis in the 0-20 cm layer revealed the following characteristics: pH ($CaCl_2$): 4.8; P: 13.7 mg dm^{-3}; K: 0.04 cmol$_c$ dm^{-3}; Ca^{2+}: 2.0 cmol$_c$ dm^{-3}; Mg^{2+}: 0.6 cmol$_c$ dm^{-3}; Al^{3+}: 0 cmol$_c$ dm^{-3}; H + Al: 2.9 cmol$_c$ dm^{-3}; SB: 2.60 cmol$_c$ dm^{-3}; CEC: 5.50 cmol$_c$ dm^{-3}; V: 48 %.

Based on the soil chemical analysis, fertilization recommendations followed Brasil et al. (2020) for leafy vegetables. For base dressing, single superphosphate (18 % of P_2O_5) was applied as phosphorus source, while urea (45 % of N) and potassium chloride (60 % of K_2O) were used for topdressing at 7 and 14 days after transplanting (DAT). The plants were irrigated twice daily, and crop treatments such as weeding were carried out as needed.

At 20 DAT, the following traits were assessed: days to foliar differentiation: determined by counting the number of days from transplanting to the onset of foliar differentiation of the floral stalk (Figure 1A);

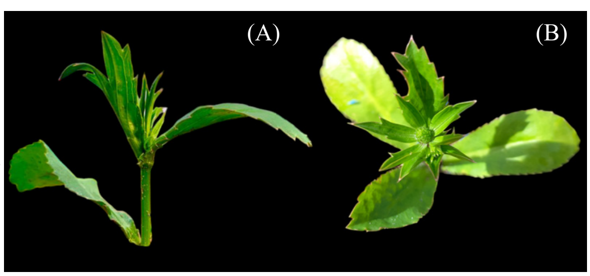

Figure 1. *Eryngium foetidum* foliar differentiation (A) and floral stalk emergence (B).

days to flowering: obtained by counting the number of days from transplanting to the emergence of the first capitulum (Figure 1B); number of leaves during the vegetative phase: determined by counting the number of leaves per plant at the onset of foliar differentiation of the floral stalk; number of leaves during the reproductive phase: determined by counting the number of leaves per plant at the onset of the emergence of the first capitulum.

Seed harvesting began at 67 DAT and was conducted in a staggered manner as the capitula changed color from green to brown (Figure 2). The following traits were assessed during the harvest: number of leaves at harvest: determined by counting the number of leaves per plant; number of tillers per plant: determined by counting the number of tillers per plant; number of flowering stalks per plant: determined by counting the number of flowering stalks per plant; number of seeds: determined by counting the number of seeds per inflorescence order; 100-seed weight: obtained by weighing two replicates of 100 seeds per inflorescence order; seed production per plant: established by weighing the seeds per inflorescence order; seed yield: calculated as the ratio between the seed weight per order and the area occupied by the plant (Ferreira et al. 2021).

The collected data were submitted to analysis of variance (Anova) assumptions, including outlier detection, normality of residuals, homogeneity of variances and independence of residuals. Next, a correlation network analysis was performed using the corrr (Kuhn et al. 2022) and ggraph (Pedersen 2024) packages.

All the data were processed and statistically analyzed using the R programming language, version 4.3.3 (R Core Team 2024).

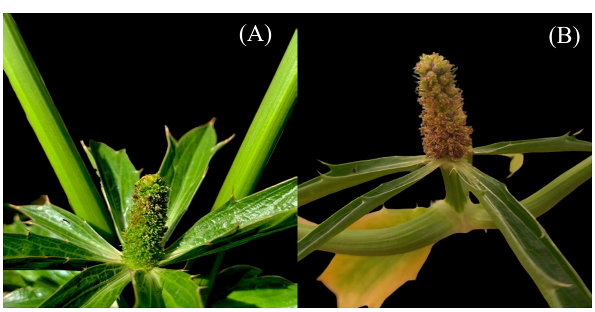

Figure 2. *Eryngium foetidum* inflorescence. Green capitula (A) and capitula transitioning from green to brown (B).

The average temperature, relative humidity and total rainfall recorded during the Amazon chicory cultivation were 26.6 ºC, 89.6 % and 2,063 mm (13.6 mm day^{-1}), respectively (Figure 3). These climate conditions were deemed suitable for plant development, given the crop's adaptation to tropical climates, characterized by high temperatures and humidity (Rodrigues et al. 2022).

The Amazon chicory plants (Table 1) began to emit their floral stalk at around 26 days after field establishment. By approximately 32 days of cultivation, the first capitulum (first order) could be observed.

During the seed production phase, the floral stalk with first-order inflorescence produced an average of 0.036 g of seeds plant^{-1}. As the number of inflorescence orders increased, so did the seed production, reaching an average of 0.25 g of seeds plant^{-1} up to the fourth order, corresponding to an average yield of 6.23 g m^{-2} (Table 1).

It is important to note that the seed production for Amazon chicory plants increased with the number of inflorescence orders (Table 1). This result is related to its dichotomous growth, given the progressive increase in the number of capitula, which doubles at each stage, leading to a significant number of seeds. This is common in Apiaceae species, which exhibit an indeterminate flowering pattern (Singh et al. 2014, Carruba & Lombardo 2020, Cardozo et al. 2021).

Thus, in order to maximize the Amazon chicory seed production for cultivation purposes, it is essential to understand the relationships among components. To that end, a correlation network analysis was performed, where the edges between

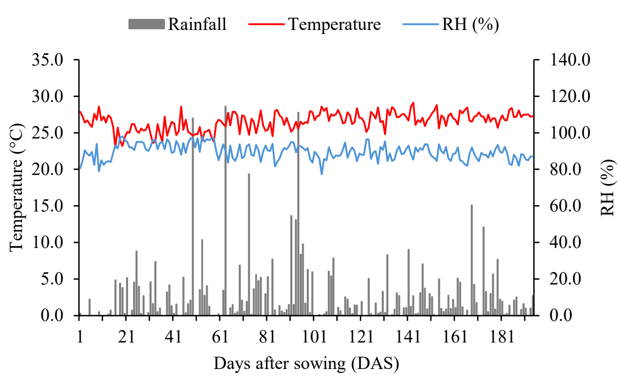

Figure 3. Daily average temperature, relative humidity (RH) and rainfall from January to July (Amazonian winter) 2023, for Amazon chicory (*Eryngium foetidum*) cultivation.

Table 1. Average number of days to foliar differentiation (DFD), days to flowering (DF), number of leaves in the vegetative phase (NLV), number of leaves in the reproductive phase (NLR), number of leaves at harvest (NLH), number of tillers per plant (NTP), number of flowering stalks per plant (NFSP), number of seeds (NS), 100-seed weight (HSW; g), seed production per plant (SPP; g plant^{-1}) and seed yield (SY; g m^{-2}) for Amazon chicory (*Eryngium foetidum* L.).

Capitula order	DFD	DF	NLV	NLR	NLH	NTP	NFSP	NS	HSW	SPP	SY
1st	29.33	35.16	5.66	5.00	16.16	2.50	3.50	56.33	0.07	0.036	0.82
2nd	24.50	29.16	5.33	5.66	14.83	2.33	4.00	158.83	0.09	0.081	2.01
3rd	24.66	30.00	5.16	5.50	14.16	2.66	4.50	217.83	0.07	0.185	4.64
Mixture	26.50	32.66	5.66	5.16	14.66	2.33	4.66	774.66	0.08	0.698	17.44
Overall mean	26.25	31.75	5.46	5.33	14.96	2.46	4.17	301.92	0.08	0.250	6.23
Standard error	1.15	1.09	0.10	0.18	0.75	0.13	0.18	58.56	1.39	0.890	1.36

the nodes are colored according to the correlation sign: blue for positive correlations and red for negative correlations. The edge thickness represents the absolute magnitude of the correlations, that is, thicker edges denote stronger correlations (Figure 4).

This network showed a strong positive correlation between seed yield and seed yield × number of seeds (r = 0.99; p-value = 0.0000), number of tillers per plant × number of seeds (r = 0.99; p-value = 0.0000) and number of tillers per plant × seed yield (r = 1.00; p-value = 0.0000), forming a group of highly interrelated traits (Figure 4). This relationship occurs because number of tillers per plant and seed yield are derived from the total seed weight. Thus, as the order number increases, so does the number of seeds, thereby improving seed production and yield (Table 1).

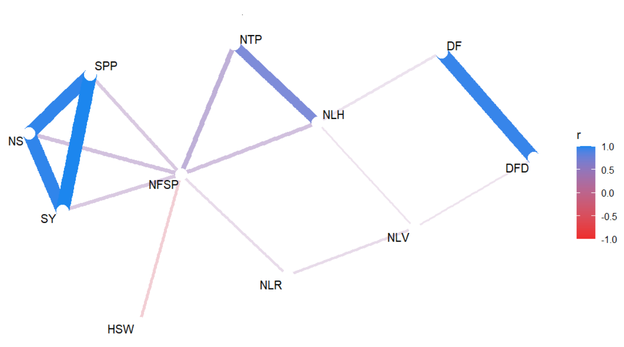

Figure 4. Correlation network for seed production components of Amazon chicory (*Eryngium foetidum*). SPP: seed production per plant (g plant^{-1}); NS: number of seeds; SY: seed yield (g m^{-2}); NFSP: number of flowering stalks per plant; HSW: 100-seed weight (g); NTP: number of tillers per plant; NLH: number of leaves at harvest; NLR: number of leaves in the reproductive phase; NLV: number of leaves in the vegetative phase; DF: days to flowering; DFD: days to foliar differentiation.

According to Ekpong & Sukprakarn (2006), the highest *E. foetidum* seed yield is obtained at the seventh and eighth orders. However, the maximum number of seeds per capitulum occurs up to the sixth order, with a decline in the subsequent orders. These results are expected for umbelliferous species due to the variability in capitula order and the continuous production of inflorescences.

A strong, positive and significant correlation was observed for days to foliar differentiation × days to flowering (r = 0.96; p-value = 0.0000). These components are interrelated, since they reflect the interval in days between the onset of floral stalk emergence and the appearance of the first capitulum (first order), which occurred at around 26 and 31 days after transplanting, respectively (Table 1).

These traits may be important indicators of early *E. foetidum* bolting. It is necessary to underscore that once the floral stalk emerges, photoassimilates are redirected to inflorescence and seed development, causing a decline in leaf production (Rodrigues et al. 2022).

The components number of tillers per plant × number of leaves at harvest (r = 0.75; p-value = 0.0000) were positively correlated (Figure 4), indicating that the number of tillers per plant increases as the number of leaves at harvest rises. This result is associated with the source-sink relationship, given that a larger leaf area provides greater light interception, thereby boosting photosynthate production, which is distributed between the plant's organs to sustain growth and development (Taiz et al. 2017).

In this respect, the number of leaves directly and indirectly affected the seed production, since it is related to dry matter accumulation and tiller development, which are associated with the emergence of new flowering stalks and inflorescences.

A moderate, positive and significant correlation was observed for the number of flowering stalks per plant × number of tillers per plant (r = 0.47; p-value = 0.0207) (Figure 4). Notably, the number of flowering stalks per plant directly influenced the number of seeds (r = 0.38; p-value = 0.0644), which is determined by the number of capitula. Thus, it can be inferred that the number of flowering stalks per plant is a critical production component for Amazon chicory, since it results in a greater seed yield.

With respect to the 100-seed weight, the correlogram showed that the pattern of this variable reflected its weak and negative correlation with number of flowering stalks per plant (r = -0.35; p-value = 0.0888), number of leaves in the vegetative phase (r = -0.28; p-value = 0.1786), number of tillers per plant (r = -0.17; p-value = 0.4388), number of leaves at harvest (r = -0.13; p-value = 0.5349), days to flowering (r = -0.10; p-value = 0.6324) and days to foliar differentiation (r = -0.059; p-value = 0.7849) (Figure 4). This negative correlation between 100-seed weight and number of flowering stalks per plant and number of tillers per plant suggests that the simultaneous emergence of tillers and flowering stalks may create a competition for photoassimilates, altering their redistribution. Based on these findings, management strategies such as pruning should be adopted to standardize the flowering stalks, increase carbohydrate and protein accumulation, and anticipate seed maturation in selected capitula (Campos et al. 2019).

Furthermore, the unequal distribution of photoassimilates and nutrients between the vegetative and reproductive organs, due to the increase in the number of leaves, tillers, flowering stalks, capitula and seeds, may alter seed translocation and distribution, resulting in a lower seed weight (Nakagawa 2014). A decrease in seed weight and the lack of correlation with other *E. foetidum* traits were also reported by Ekpong & Sukprakarn (2006) and Moraes et al. (2021).

Regarding the number of leaves during the vegetative and reproductive phase, the correlation with other variables was weak (r < 0.33) (Figure 4). This result may be associated with the assessment time, which occurred, on average, up to 31 days after transplanting, during which the plants produced an average of five leaves per plant. No significant differences were observed between growth and reproductive phases for this trait (Table 1). Additionally, seedling quality and climate conditions during cultivation may have contributed to the slower growth (Souza et al. 2020).

The correlation network demonstrated that changes in seed production components for Amazon chicory can influence the individual behavior of each component, leading to direct and indirect gains or losses due to their interdependence. These factors can determine seed yield and biomass gains through their flexibility and self-compensatory capacity (Nakagawa 2014, Carruba & Lombardo 2020). As such, understanding the degree of correlation among agronomic traits is crucial, since it enables the identification of characteristics that can maximize correlated variables (Cabral et al. 2011).

The traits days to foliar differentiation and days to flowering can be used to identify early *Eryngium foetidum* bolting. The components number of tillers per plant, number of flowering stalks per plant, number of leaves at harvest and number of seeds contributed most, both directly and indirectly, to the *E. foetidum* seed yield. By contrast, the number of leaves during the vegetative and reproductive phases can be disregarded, since they are not related to seed yield.

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