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Graphical analysis of genetic variability in essential oil profiles of *Anethum graveolens* L.

Naser Sabaghnia*[1], Mehdi Mohebodini[2], Karim Farmanpour-Kalalagh[3]

[1] Department of Plant Production and Genetics, Faculty of Agriculture, University of Maragheh, Iran
[2] Department of Horticultural Science, Faculty of Agricultural Science and Natural Resources, University of Mohaghegh Ardabili, Ardabil, Iran
[3] Department of Horticultural Science, Faculty of Agriculture, Tarbiat Modares University, Tehran, Iran

Original paper

Abstract: Medicinal and aromatic plants have long played a vital role in health, wellness, and culinary practices. This research aimed to assess the genetic variation in essential oil content and its components among five local landraces of dill (*Anethum graveolens* L.) from Mashhad, Ardabil, Parsabad, Bushehr, and Esfahan. Essential oil and its composition, including β-pinene, α-terpinene, β-phellandrene, carvacrol, dillapiole, neophytadiene, and hexahydrofarnesyl acetone, were analyzed. The drawn biplot explained 90% of the variation, clearly depicting genotype-trait relationships. It revealed both additive and crossover interactions, suggesting that genotype rankings were trait-dependent. Among the evaluated genotypes, Bushehr exhibited the highest essential oil yield and quality, followed by Esfahan, Mashhad, Ardabil, and Parsabad. The strongest positive correlations were observed between β-phellandrene, dillapiole, and essential oil content, while the association between α-terpinene and β-pinene was more intricate and less pronounced. The superior performance of the Bushehr genotype makes it a prime candidate for future breeding initiatives. Furthermore, carvacrol emerged as the most discriminative trait for disticnting among genotype. The study also revealed that increased in essential oil content in *A. graveolens* was associated with higher production of dillapiole and β-phellandrene, coupled with reduced levels of β-pinene, neophytadiene, and hexahydrofarnesyl acetone.

Keywords: Biplot, carvacrol, distinction ability, ideal genotype.

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Correspondence
Prof. Naser Sabaghnia
sabaghnia@yahoo.com

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Introduction

Medicinal and aromatic plants play a crucial role in health, wellness, and culinary traditions. Among them, dill (*Anethum graveolens* L.), an annual herb from the Apiaceae family, is widely cultivated for its culinary, cosmetic, and medicinal applications. Native to southwestern and central Asia(Yaldız et al., 2018) , it is grown in various regions of Iran like shourthen, northeastern, northwestern, and central areas.

Dill's leaves and seeds are used in food, cosmetics, and health products. Its seeds and flowers contain high levels of essential oils, fatty acids, phenolic acids, and flavonoids, while stems and leaves have lower concentrations (Goodarzi et al., 2016). The composition of its essential oil, particularly α-phellandrene and germacrene D, varies with drying temperature, origin, and extraction methods. These compounds contribute to dill's antioxidant, antimicrobial, and antidiabetic properties, rendering it a valuable natural additive in pharmaceutical and health-related industries.

Dill's essential oil composition and bioactivity are influenced by genetic and environmental factors, as well as post-harvest practices (Ghassemi-Golezani et al., 2022). This variation, particularly linked to genetic diversity, has attracted significant research interest, highlighting its potential for optimizing therapeutic and economic benefits.*A. graveolens*.

Genetic diversity forms the backbone of plant adaptability, resilience, and metabolic versatility. In the case of *A. graveolensA. graveolens*, the genetic variability among populations and genotypes significantly influences the synthesis and accumulation of essential oil components (Biesiada et al., 2019). This variability is critical for several reasons; because it governs the plant's ability to thrive in diverse environmental conditions, including variations in soil type, climate, and water availability. Also, genetic diversity influences the production of specific phytochemicals, which are key to the plant's medicinal efficacy and economic value. Finally, understanding the genetic factors underlying essential oil composition is essential for breeding programs aimed at enhancing specific traits, such as higher essentail oil yield, improved bioactivity, or tolerance to environmental stressors (Gurav et al., 2022). The characteristics of *A. graveolens* essential oil during drying are influenced by factors such as drying method and temperature. Understanding the effects of geographical origin on essential oil yield and composition is vital, given dill's medicinal significance. Phytochemical diversity in dill is shaped by genetic and environmental factors, including location, soil, climate, water, harvest timing, growth stage, and plant parts used.

Global studies on dill have demonstrated substantial differences in essential oil profiles among populations from various regions. For instance, research has shown that *A. graveolens* cultivated in Mediterranean climates tends to produce essential oils with higher concentrations of carvone (El-Zaeddi et al., 2016), while plants grown in arid or semi-arid regions may exhibit increased levels of limonene and α-phellandrene (Amanpour et al., 2017). These differences are often attributed to genetic factors, as well as the interaction between genotype and environment. Such findings underscore the importance of exploring the genetic diversity of *A. graveolens*, particularly in regions with diverse ecological conditions. Iran is a region of considerable ecological diversity, encompassing a wide range of climates, altitudes, and soil types. This variation creates a unique opportunity to study the genetic and environmental influences on dill essential oil composition (Biesiada et al., 2019). The northeastern regions of Iran, with their arid climate and alkaline soils, may favor the production of certain terpenoids, while the more temperate conditions of the northwestern regions could enhance the biosynthesis of phenolic compounds (Farmanpour Kalalagh et al., 2023). Such regional differences provide a valuable framework for examining how genetic and environmental factors interact to shape the essential oil profile of dill. This study examines how various landraces influence the essential oil, and its composition in some Iranian *A. graveolens* genotypes.

Materials and Methods

Trial and traits

In the present study, five local landraces of dill (*A. graveolens* L.), originating from diverse regions of Iran, were evaluated. These regions included Mashhad (36° 19′ N, 59° 32′ E; altitude 995 m) in the northeast, Ardabil (38° 15′ N, 48° 18′ E; altitude 1500 m) and Parsabad (39° 38′ N, 47° 54′ E; altitude 47 m) in the northwest, Bushehr (28° 55′ N, 50° 51′ E; altitude 8 m) in the southern part of the country, and Esfahan (32° 39′ N, 51° 40′ E; altitude 1590 m) in the central region. The research was conducted at a designated experimental field station in Ardabil, Iran, which is characterized by loamy soil. The research aimed to evaluate the genetic variation and phytochemical diversity of essential oils extracted from these landraces to assess their potential for medicinal and agricultural applications. Seeds of the five dill genotypes were collected and subjected to rigorous seed vigor testing to ensure uniformity in germination and initial growth potential. The seeds were sown in a research field following a completely randomized block design using three replications to ensure reliability. The field experiment was carefully managed, with plants irrigated twice a week to maintain optimal soil moisture levels conducive to dill growth. The plants were allowed to grow until they reached the full flowering stage, as this stage is known to yield the highest concentration of essential oils in dill. At this point, the leaves and flowers were harvested for subsequent analysis. The dried samples were ontined in room temprute (25°C) for thrre days. The extracted essential oil was injected into a GC-MS system, which separates and identifies chemical constituents. A capillary column was used to achieve high-resolution separation. The sample was heated in a controlled manner, and components were detected based on their retention times and mass spectra. The primary compounds, including β-pinene (B-Pinene), α-terpinene (A-Terpinene), β-phellandrene (B-Phell), carvacrol, dillapiole, neophytadiene (Neoph), and hexahydrofarnesyl acetone (Hex-Ace), were identified using reference standards and spectral libraries. The relative percentage of each compound was calculated using peak area normalization (Farmanpour Kalalagh et al., 2023). Essential oil yield (EO) was determined as the percentage of extracted oil relative to the dry weight of the plant material.

Statistical analysis

The obtained data were subjected to normality testing using the Anderson-Darling test. Once data normality was confirmed, further statistical evaluations were conducted to examine the genetic and phytochemical variability among the dill genotypes. The principal component analysis (PCA) results were visualized using a genotype × trait interaction biplot model, which offers a graphical representation of the relationships between genotypes and traits. This analysis was performed using the equation:

$$\frac{x_{ij} - y_j}{SD_j} = \sum_{n=1}^{2} \lambda_n \xi_{in} \eta_{jn} + R_{ij}$$

where x_{ij} is showing the performance of genotype i in trait j, y_j is the average of all x_{ij} for trait j, SD_j is the standard deviation for trait j, λ_n is the singular value for PCAn, ξ_{in} and η_{in} are scores for genotypes i and trait j on PCAn, respectively, and R_{ij} is the residual of model. To compute symmetrical scales of traits and genotypes, the eigenvalue is adjusted through vectors' absorption. This adjustment ensures that the testers and entries are displayed in a normal and standardized manner. This approach also allows for a clear graphical representation of the relationships among genotypes and traits, along with their interactions, providing insightful visual interpretations. For the data scaling and centering process, specific parameters were applied to ensure proper analysis. Scaling was set to 1, which ensures that the data is appropriately adjusted for comparative analysis. Centering was applied using a factor of 2, allowing the data to be centered around the mean of each variable. The singular value decomposition (SVD) method was employed with an SVP value of 2 to calculate the singular scores. This method enables a deeper understanding of the underlying structure of the data. Additionally, an SVP value of 1 was used to generate singular scores that are ideal for visually interpreting the correlations among genotypes.

Results

The genotype × trait interaction biplot model explained 61% and 29% of the variation in the standardized two-way dataset (Figure 1), respectively, highlighting a substantial portion of the variation that underscores the direct associations among traits. To facilitate the interpretation of these relationships, vectors were plotted from the origin of the graph to each trait.

This approach allowed for the visualization of trait interactions, regarding additive and crossover interactions, indicating that the ranking of genotypes across traits may shift.

The biplot model demonstrated both additive and crossover interactions, indicating that the ranking of genotypes across traits may shift. This observation aligns with the findings of Sabaghnia and Jamalluddin et al. (2021) in *Triticum aestivum* L. and Yari et al. (2018) in *Secale cereale* L., who noted the complexity of genotype selection when entry-by-tester interactions are not considered. In the current study, the biplot model, as recommended by Sedghiyeh et al. (2025), proved to be an effective tool for exploring and visualizing genotype-trait relationships. The model successfully captured a remarkable 90% of the total variability, with trait associations determined by the cosine of the vectors. Specifically, a cosine of 0° corresponds to +1, 90° to 0, and 180° to -1. The biplot presented considerable variability, as indicated by the long vectors (Figure 1). Notably, β-phellandrene (B-Phell), dillapiole, and essential oil (EO) showed a positive association, as evidenced by the relatively close angles of their vectors. Similarly, neophytadiene (Neoph) and β-pinene (B-Pinene) were positively correlated due to their acute angles. In contrast, α-terpinene (A-Terpinene) was positioned at relatively right angles to B-Phell and EO, as well as to Neoph and B-Pinene, indicating no strong positive or negative relationships among them (Figure 1). This pattern was similarly observed in the interactions involving carvacrol, which exhibited negative associations with the aforementioned groups of traits. A notable negative correlation was observed between carvacrol and A-Terpinene, as their vectors formed an obtuse angle.

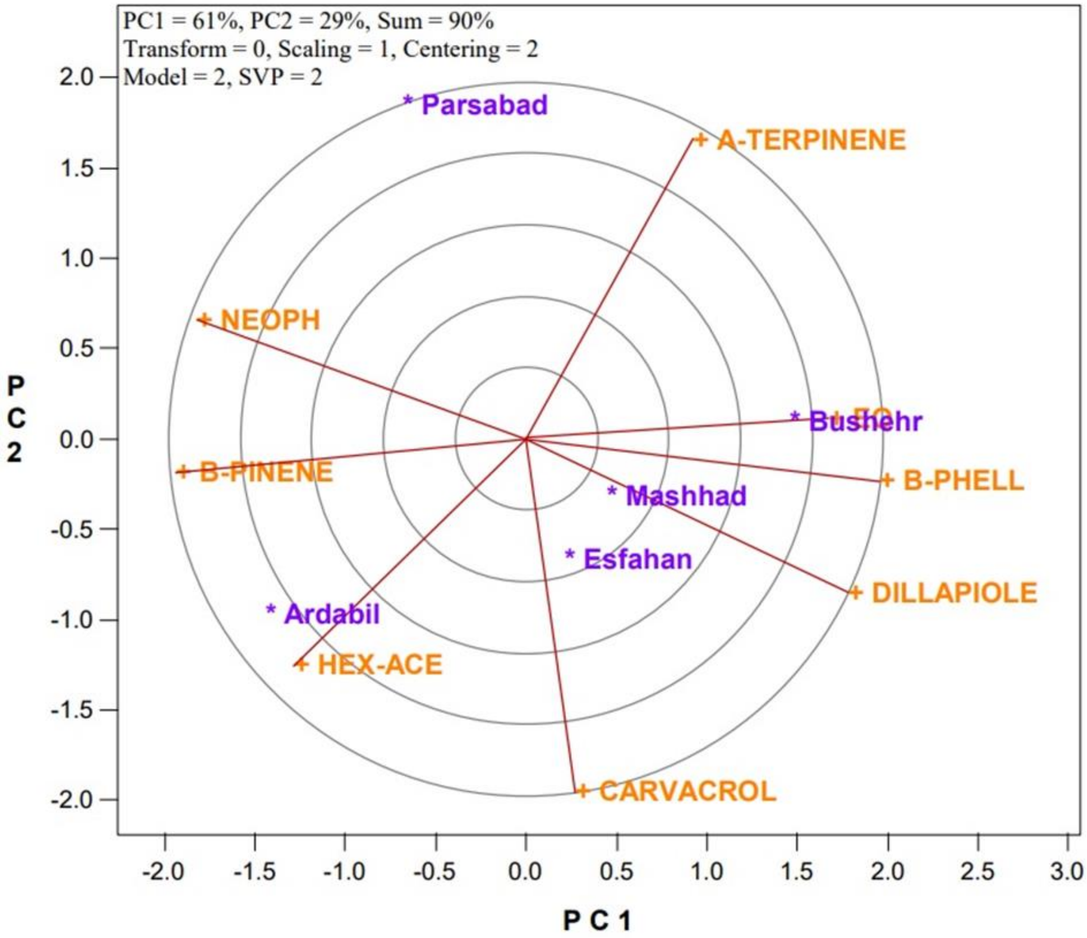

Figure 1. The relationships among traits of dill (*Anethum graveolens* L.) genotypes.

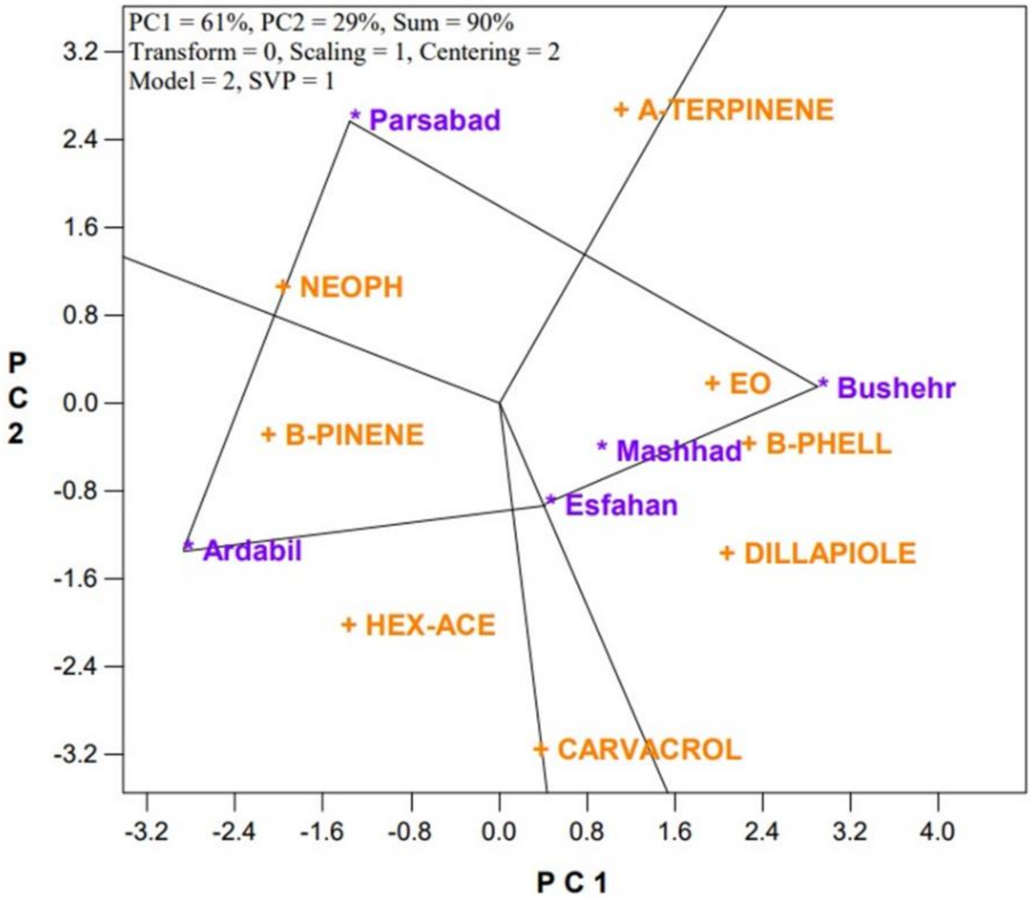

Figure 2. Superior phytochemical traits of elite Anethum graveolens genotypes

Additionally, a significant negative association was noted between B-Phell and EO with Neoph and B-Pinene, and between hexahydrofarnesyl acetone (Hex-Ace) and A-Terpinene (Figure 1). The results suggest that increasing the levels of essential oil in *A. graveolens* enhances the production of dillapiole and β-phellandrene, while concurrently reducing the generation of β-pinene, neophytadiene, and hexahydrofarnesyl acetone. However, these changes did not significantly alter the levels of carvacrol or α-terpinene. The fitted biplot model thus provided a clear visual representation of trait associations in *A. graveolens*, supporting the findings of Farmanpour Kalalagh et al. (2023), who reported positive correlations between β-phellandrene, dillapiole, and essential oil, as well as between neophytadiene and β-pinene. It is noteworthy that while the biplot method visually illustrates trait associations based on the overall structure of the dataset, correlation coefficients specifically measure the direct interrelationships of traits. Therefore, the results from the biplot may not always align precisely with the direct pairwise correlations between traits.

Figure 2 illustrates how the biplot model aids in the evaluation of genotypes based on their trait performance, identifying those that excel in specific traits and thereby serve as suitable candidates for breeding or cultivation. A tetragon was constructed with perpendicular lines to its sides, facilitating easier comparisons among the genotypes. Four key genotypes; Ardabil, Bushehr, Esfahan, and Parsabad; were identified as the vertex genotypes. Genotype Ardabil exhibited the highest values for hexahydrofarnesyl acetone (Hex-Ace) and β-pinene (B-Pinene), whereas genotype Parsabad showed superior performance in neophytadiene (Neoph) and α-terpinene. Genotype Bushehr, on the other hand, recorded the highest values for β-phellandrene (B-Phell), dillapiole, and essential oil (EO). Carvacrol was positioned at the boundary between the vertex genotypes of Ardabil and Esfahan (Figure 2). The performance of genotype Mashhad was found to be similar to that of genotype Bushehr, albeit with relatively lower levels of the aforementioned traits. The classification of these genotypes into four distinct groups highlights their genetic diversity, which can be attributed to their adaptation to different geographical regions. This variation among local landraces is consistent with findings by Mohebodini et al. (2024), who utilized the genotype × trait interaction biplot model to assess genetic variation in ten native *Portulaca oleracea* L. genotypes, reporting similar distinct variations among local landraces.

Figure 3 illustrates the position of the ideal genotype, with the genotypes closest to its location being considered the most favorable. Based on this assessment, the *A. graveolens* genotypes were ranked as follows: Esfahan > Mashhad > Bushehr > Ardabil > Parsabad, with Esfahan identified as the most desirable and Parsabad as the least desirable. The identification of these ideal genotypes is crucial for future genetic improvement programs in dill. This issue is particularly given that essential oil content and its quality characteristics often exhibit low or even negative correlations in many vegetable crops. Thus, the application of multivariate statistical tools, combined with graphical representations, is essential for identifying ideal genotypes and refining breeding strategies for *A. graveolens*. In other words, using Esfahan as the ideal genotype provides a reliable benchmark for evaluating the yield of essential oil and its biochemical components. The results obtained from Esfahan are considered more reliable compared to those of the other genotypes due to its desirable characteristics.

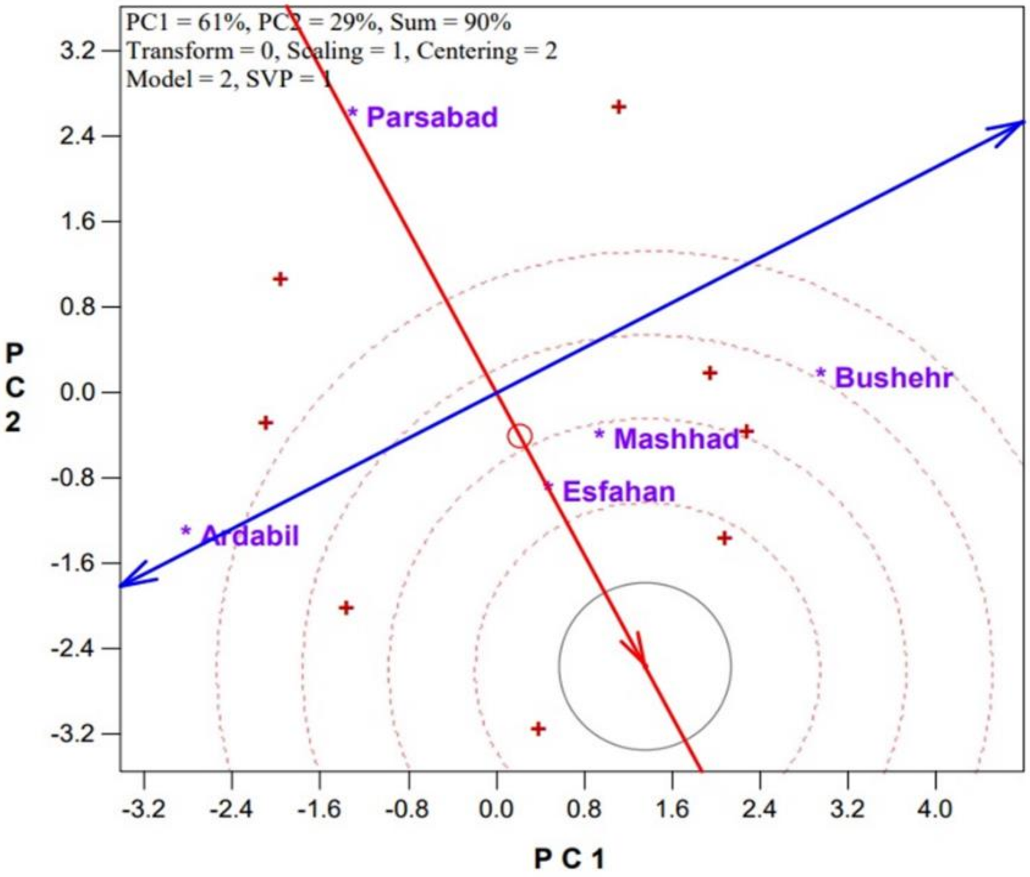

Figure 3. The ideal genotype of dill (*Anethum graveolens* L.).

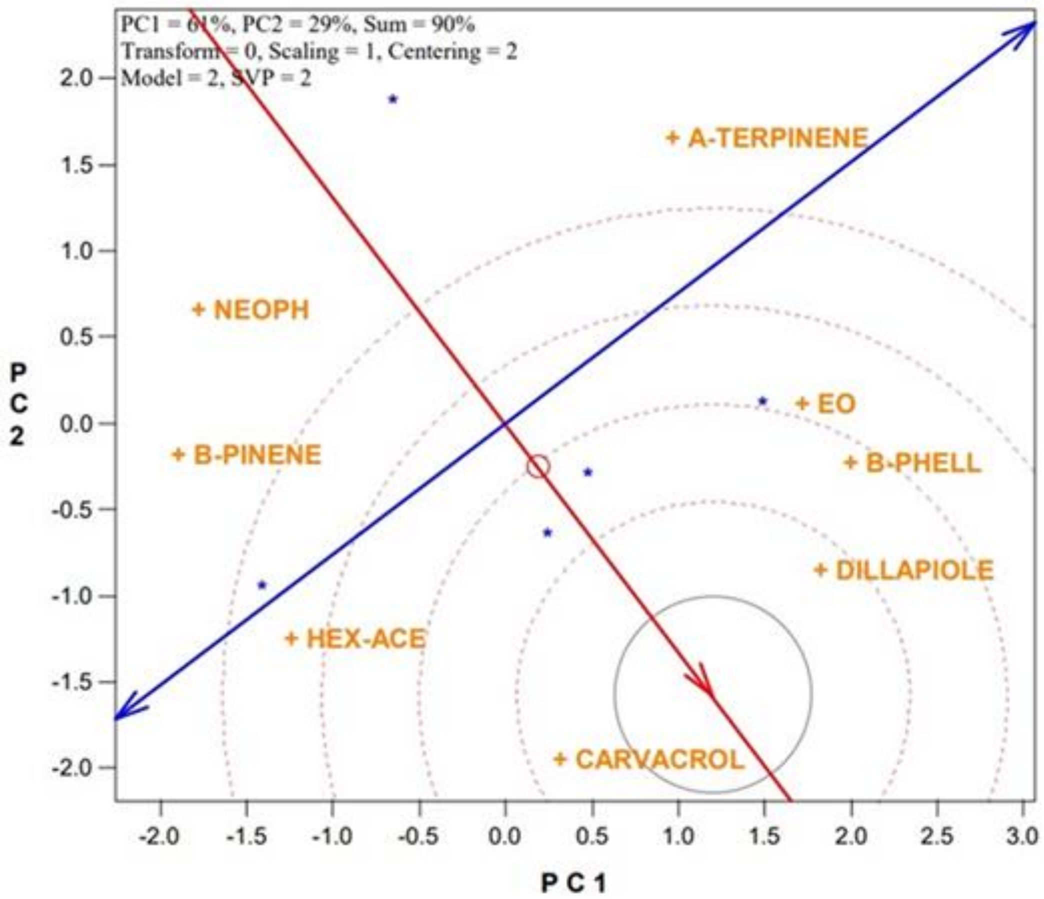

Figure 4. Target traits for ideal dill (*Anethum graveolens* L.) genotype selection.

Sabaghnia et al. (2024) suggested that ideal genotypes, such as Esfahan, should be used as reference genotypes in future studies to better understand genetic variability across traits, as they demonstrate a high potential based on the traits evaluated. The discriminative property of a trait is determined by the value of its standard deviation, with higher values indicating a greater ability to distinguish between genotypes. This property is illustrated by the hypothetical ideal trait shown in Figure 4, where traits closer to the ideal location exhibit high discriminative power, while those further away are less effective. Based on the current analysis, carvacrol is identified as the most discriminative trait. In contrast, traits such as β-phellandrene, dillapiole, hexahydrofarnesyl acetone, and essential oil demonstrate above-average discriminative potential, indicating their effectiveness in differentiating *A. graveolens* genotypes (Figure 4). Conversely, traits like α-terpinene, β-pinene, and neophytadiene show low discriminative potential and are therefore not recommended for future investigations. The typical ability of a trait, reflecting its symbolic role, is evaluated by the angle between the trait's vector and the axis of the average trait. Smaller angles indicate greater typical ability. In this context, carvacrol, followed by dillapiole, exhibits the highest typical ability, while hexahydrofarnesyl acetone shows a larger angle with the axis, reflecting its lower typical ability. When evaluating traits, ideal genotypes should be able to differentiate from other genotypes based on the representativeness of the ideal trait. Biplot analysis provides valuable insights by considering the traits with strong representativeness, offering useful information for future selection and breeding efforts.

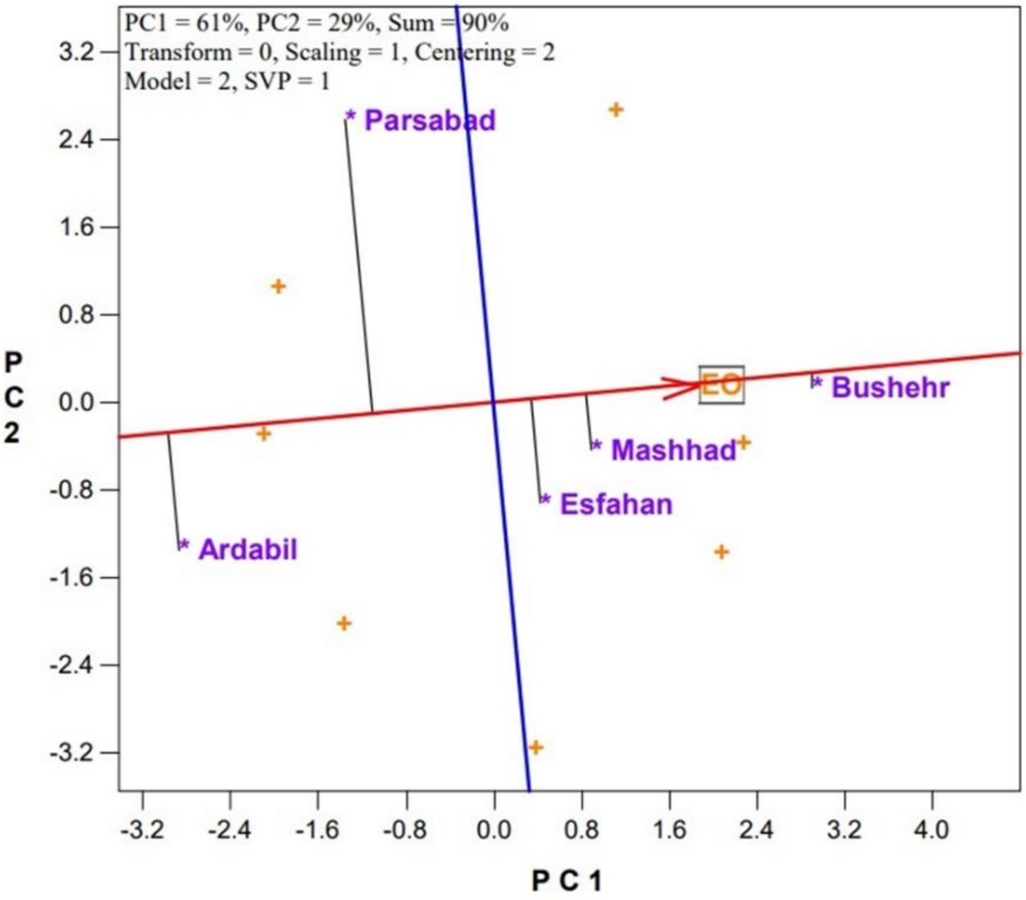

Figure 5. The performance of dill (Anethum graveolens L.) genotypes for essential oil (EO) production.

Figure 5 assesses the performance of *Anethum graveolens* genotypes in terms of EO yield, with the horizontal axis representing EO content and the direction indicated by an arrow. Genotype Bushehr demonstrated the highest performance for essential oil yield, while genotype Ardabil exhibited the lowest. Genotypes Esfahan and Mashhad showed above-average performance for EO, as they lie above the average axis, while genotype Parsabad was identified as below-average in terms of essential oil production. The distance of each genotype from the horizontal axis serves as an indicator of variability; smaller distances suggest minimal variance, making those genotypes preferable for selection. Fortunately, high-yielding genotypes such as Bushehr, Esfahan, and Mashhad are recommended for their low variance. In contrast, genotypes Parsabad and Ardabil, which exhibit lower essential oil yields and are positioned further from the horizontal axis, demonstrate greater variability and are considered less desirable. Evaluating *A. graveolens* genotypes is essential for preventing genetic erosion and optimizing genetic improvement efforts. Our study revealed considerable variation among the examined genotypes, a finding that aligns with previous studies highlighting significant diversity within dill populations (Weisany et al., 2015; Farmanpour Kalalagh et al., 2023). The genotype × trait interaction biplot model indicated a high level of variability and confirmed the presence of both simple and complex interactions between genotypes and traits. Similar patterns of genotype-trait interactions have been observed in various vegetable crops, such as *Spinacia oleracea* (Sabaghnia et al., 2015) and *Amaranthus tricolor* (Jamalluddin et al., 2021). These interactions led to differing genotype rankings across traits, complicating the selection of the most desirable genotypes. Ignoring genotype × trait interactions can complicate the selection process due to their influence on the performance of genetic components. However, the obtained results were according to a single trial, and outcomes may vary with other datasets. To address this, an alternative model suggests replacing the first principal component with predictions derived from a linear regression model applied to tester-centered data on genotype effects, which improves the interpretability of the model.

Discussion

The present study explored the genetic variability of essential oil components across five different genotypes of *A. graveolens*, originating from various regions of Iran. These findings align with previous reports indicating significant differences in the profile of essential oil expected from geographically distinct populations of medicinal plants (Karimi et al., 2020). The analysis of essential oil components, using genotype × trait interaction biplot models, revealed notable interactions between genotype and trait, emphasizing the complex nature of selecting the most favorable genotypes with high essential oil in *A. graveolens*. One of the key outcomes of this study was the identification of the Bushehr genotype as the most favorable for high essential oil production. Bushehr exhibited elevated levels of β-phellandrene and dillapiole, both of which are considered valuable bioactive compounds. This finding is consistent with those of (Ozliman et al., 2021), who highlighted the variation in essential oil yields among different genotypes of *A. graveolens*. Additionally, this result aligns with similar studies conducted on other medicinal plants, such as fennel (*Foeniculum vulgare*) and basil (*Ocimum gratissimum*), where genotype variability significantly influenced essential oil content (Shojaiefar et al., 2015; Sharma et al., 2024). Furthermore, current analysis revealed that increasing essential oil production in *A. graveolens* was related by increasing in the levels of dillapiole and β-phellandrene, while the concentrations of β-pinene, neophytadiene, and hexahydrofarnesyl acetone were reduced. These findings are significant as they suggest that optimizing essential oil production in dill can lead to an improved balance of bioactive compounds that enhance its therapeutic properties. Similar correlations between essential oil content and specific bioactive compounds have been reported in *A. graveolens* and other medicinal plants (Gholizadeh et al., 2021; Sabaghnia et al., 2024), where increases in specific oil components correspond to better pharmacological activity. The use of the genotype × trait interaction biplot model in this study proved invaluable for exploring and visualizing the relationships between genotypes and their associated traits. The biplot clearly demonstrated how genotype rankings across traits could change, indicating the complex nature of genotype × trait interactions. This aligns with (Sabaghnia et al., 2015), who highlighted the difficulties in selecting genotypes for breeding without considering these interactions. The use of the genotype × trait interaction biplot allows for the visualization of both additive and crossover interactions, providing breeders with a tool to evaluate multiple traits simultaneously and make more informed decisions.

In terms of discriminative power, carvacrol emerged as the most effective trait for differentiating between genotypes, with its position on the biplot indicating a strong association with high essential oil content and favorable bioactive profiles. Current results are in good consistent with past reports, which has confirmed carvacrol as a critical compound in various medicinal plants, including *Origanum vulgare* and *Thymus vulgaris*, where it is known for its antioxidant and antimicrobial properties (Naghdi Badi et al., 2017). By focusing on carvacrol, breeders can identify and select genotypes that are more likely to produce high-quality essential oils with therapeutic potential. The results from the discriminative and representative property analysis also highlighted the role of carvacrol in guiding future breeding efforts. As a highly discriminative trait, carvacrol can serve as a key marker in genetic improvement programs aimed at enhancing essential oil yield and quality. This approach is supported by similar findings in other crops, where the identification of key discriminative traits has facilitated more targeted breeding strategies.

Another important observation in our study was the identification of Esfahan as the most ideal genotype for essential oil production. The proximity of Esfahan to the ideal genotype position on the biplot indicated its superior performance in producing high-quality essential oil. This aligns with previous research that has used ideal genotype modeling to assess the genetic potential of medicinal plants for essential oil production (Sabaghnia et al., 2024). The potential to identify ideal genotypes is critical for the development of new cultivars with enhanced essential oil performance, particularly in crops like dill, where essential oil yield and quality often have low or even negative correlations with other traits. The variability observed in the essential oil components across the five genotypes supports the hypothesis that environmental factors, such as geographic origin and soil conditions, had a meaningful effect in generation of the phytochemical profile of *A. graveolens*. Thus, the importance of benefiting genetic as well as environmental issues in selecting genotypes for genetic improvement projects targeted at increasing essential oil production. Finally, relatively valuable insights were provided into the genetic variability of *A. graveolens* essential oil components and offers practical recommendations for breeding programs. The identification of Bushehr as the most favorable genotype, combined with the discriminative power of carvacrol and the ideal genotype modeling, offers a promising strategy for enhancing essential oil yield and quality in dill. Future research should focus on further exploring genotype × environment interactions and their effects on essential oil production, as well as investigating the stability of these traits across multiple growing seasons and locations. Moreover, integrating molecular markers associated with desirable traits, such as carvacrol, could accelerate the breeding of new cultivars with improved essential oil profiles. The usefulness of the ideal item for assessing discriminative ability has been demonstrated in studies by Baljani et al. (2015) in *Carthamus tinctorius* and Pourmohammad et al. (2025) in *Triticum durum* L.

To further highlight the superiority of essential oil compounds, it is essential to emphasize their enhancing properties, including their aroma, taste, and medicinal benefits. The bioactive components identified in this study, particularly β-phellandrene, dillapiole, and carvacrol, contribute significantly to the sensory and therapeutic qualities of dill essential oil. β-Phellandrene is known for its fresh, citrus-like scent, enhancing the aromatic complexity of dill, making it a valuable ingredient in culinary applications, flavoring, and perfumery. Dillapiole contributes a mildly spicy and warm note, further refining the oil's flavor profile. Carvacrol, widely recognized for its antioxidant, antimicrobial, and anti-inflammatory properties, enhances the oil's pharmaceutical value, making it beneficial for natural remedies and functional foods. The reduction in β-pinene, neophytadiene, and hexahydrofarnesyl acetone may contribute to a smoother, more refined essential oil profile, potentially improving consumer preference and therapeutic efficiency. By selecting superior genotypes that optimize these key compounds, breeding strategies can enhance both the sensory appeal and medicinal efficacy of dill essential oil, increasing its demand in pharmaceutical, cosmetic, and food industries.

Conclusion

Increasing essential oil content in *A. graveolens* enhances the production of dillapiole and β-phellandrene, coupled with β-pinene, neophytadiene, and hexahydrofarnesyl acetone reduction. The Bushehr genotype was identified as the most favorable, making it a strong candidate for cultivar development. Regarding discriminative and representative properties, carvacrol emerged as the most influential trait, effectively differentiating the most desirable genotypes. The results establish a foundation for targeted breeding strategies to increase both essential oil productivity and beneficial phytochemical compounds in new dill cultivars.

Supplementary Materials

No supplementary material is available for this article.

Author Contributions

Conceptualization, M.M.; methodology, M.M.; software, N.S.; validation, N.S., and N.S.; formal analysis, K.F.; investigation, K.F.; resources, K.F.; data curation, N.S.; writing—original draft preparation, N.S.; writing—review and editing, M.M.; visualization, K.F.; supervision, M.M.; project

administration, M.M. All authors have read and agreed to the published version of the manuscript.

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Conflict of Interest Statement

The authors declare no conflict of interest.

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مقاله پژوهشی

تجزیه و تحلیل گرافیکی تنوع ژنتیکی اجزای اسانس برخی از ژنوتیپ‌های شوید (*Anethum graveolens*)

ناصر صباغ نیا*[۱]، مهدی محب الدینی[۲]، کریم فرمانپور کلالق[۳]

[۱] گروه تولید و ژنتیک گیاهی، دانشکده کشاورزی، دانشگاه مراغه
[۲] گروه علوم باغبانی، دانشکده کشاورزی، دانشگاه محقق اردبیلی، اردبیل، ایران
[۳] گروه علوم باغبانی، دانشکده کشاورزی، دانشگاه تربیت مدرس، تهران، ایران

چکیده: گیاهان دارویی و معطر از دیرباز به دلیل سهم قابل توجهی که در سلامت، تندرستی و شیوه‌های آشپزی دارند، مورد توجه بوده‌اند. این تحقیق با هدف بررسی تنوع ژنتیکی محتوای اسانس و اجزای آن در پنج توده بومی شوید (*Anethum graveolens*) از شهرهای مشهد، اردبیل، پارس آباد، بوشهر و اصفهان انجام شد. اسانس و ترکیب آن، از جمله β-pinene، α-terpinen، β-phellandren، carvacrol، dillapiole، neophytadiene و hexahydrofarnesyl acetone، مورد تجزیه و تحلیل قرار گرفت. بای پلات ۹۰ درصد از تغییرات را توضیح داد و نمایش واضحی از روابط ژنوتیپ × صفت ارائه داد. مدل biplot هر دو برهمکنش افزایشی و ضرب‌پذیر را نشان داد، که نشان می‌دهد رتبه‌بندی ژنوتیپ می‌تواند در بین صفات تغییر کند. ارزیابی‌های اختصاصی ژنوتیپ نشان داد که بوشهر از نظر عملکرد و کیفیت اسانس بهترین عملکرد را داشته و پس از آن اصفهان، مشهد، اردبیل و پارس‌آباد قرار دارند. قوی‌ترین همبستگی مثبت بین β-phellandren، dillapiole و محتوای اسانس مشاهده شد، در حالی که ارتباط بین α-terpinen و β-phellandren پیچیده تر و کمتر مشخص بود. همچنین ژنوتیپ بوشهر به دلیل عملکرد برتر، بیشترین پتانسیل را برای برنامه‌های اصلاحی آتی نشان داد. علاوه بر این، کارواکرول به‌عنوان متمایزترین صفت برای تمایز بین ژنوتیپ ظاهر شد. این مطالعه همچنین نشان داد که افزایش محتوای اسانس در A. graveolens با افزایش تولید dillapiole و β-phellandren مرتبط است، در حالی که به‌طور همزمان سطوح β-pinene، neophytadiene و hexahydrofarnesyl acetone را کاهش می‌دهد.

کلمات کلیدی: بای پلات، توانایی تمایز صفات،کارواکرول، ژنوتیپ ایده‌آل.

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دکتر جونهوا پنگ،
مدیر تکنولوژی شرکت اگری ساینس اسپرینگ ولی، چین

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نویسنده مسئول
دکتر ناصر صباغ نیا
sabaghnia@yahoo.com

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