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Determination of maturity indices of fennel (*Foeniculum vulgare* Mill.) for chewing purposes

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ABSTRACT

Umbels were harvested at six different stages of maturation to determine maturity indices of fennel for chewing. Seeds harvested 35 and 40 days after anthesis had the highest overall sensory acceptability score (8.53 and 8.40) for chewing (raw seeds). Sensory analysis of fennel seeds harvested at various stages revealed that those harvested 35-40 days after anthesis (DAA) possess high quality from the consumer's perspective due to their superior appearance, flavour, texture, and taste. While delayed harvesting led to increased yield and higher concentrations of bioactive compounds such as phenols and antioxidants, but negatively impacted sensory attributes. Seed colour characteristics, including lightness, hue, and chroma, varied significantly across harvest stages, with optimal values observed at 35-40 DAA. Additionally, moisture content and total soluble solids decreased with maturity, while crude fibre content increased, potentially affecting consumer acceptability. Although higher yields (1190, 1422.6, 1435.48 kg ha^{-1}) and bioactive compounds were recorded at later harvest stages, the overall sensory appeal and balanced nutritional composition of seeds harvested at 35-40 DAA make them the optimal choice for chewing. These findings emphasize the importance of harvesting fennel seeds at optimum stage to meet specific market demands while maximizing sensory quality and nutritional value.

Key words: Harvesting stage, antioxidants, sensory, chromatic, essential oil.

INTRODUCTION

Fennel (*Foeniculum vulgare* Mill., Apiaceae) is an aromatic herb native to the Mediterranean region. In culinary traditions, essential oils and dried fennel seeds are commonly used as flavouring agents (Abdossi *et al*., 1). Eating raw immature fennel seeds after meals is a healthy habit because of the ability of fennel to keep the digestive system healthy. Fennel not only adds flavour to cooking, purifies blood, improves digestion, and prevents gas formation in stomach (Manohar *et al*., 11). Fennel oil, when consumed alone, can be used as a breath freshener and for gum health (Stanojevi´C *et al*., 19). Chewing fennel seeds as a mouth freshener after eating food is a common culture in the Indian Sub-continent. Chewing fennel seeds increases saliva pH making it a suitable anti-cariogenic agent (Manohar *et al*., 11). The primary p hyto-constituents of fennel seeds are phenols and volatile aromatic compounds (Noreen *et al*., 14). During seed maturity, constant spontaneous changes occur in aromatic plants causing variations in the biochemical constituents and essential oil compositions (Ratna *et al*., 17). Fennel has non-synchronous flowering behaviour and maturity of seeds, which leads to low productivity and inadequate quality of produce. Fennel generally gets plucked before the seed is fully ready for chewing. Compared to other harvesting stages, these seeds are more expensive since they are classified as immature delicate dark green seeds. Brown saunf is typically used as a seed and light-dark green fennel seed is used for chewing. Customers desire mature green seeds that are uniformly sized, highly delicious, free of physical or chemical contaminants, and have the ideal amount of fibre. Both domestic and international markets experience a considerable demand for these seeds, which attract premium pricing. The determination of maturity indices in fennel for chewing purposes has been the subject of very few studies so. The ideal quality of plants in the Apiaceae family depends greatly on the time of harvest, which is determined by maturity indices. These indicators help to ensure that fennel is harvested at its peak nutritional value, flavour, and scent. They include factors like seed color, nutritional value, and oil composition. While seeds harvested late (over-matured) have a shorter post-harvest life and decay quickly, seeds harvested before optimum maturity may not ripen sufficiently and may not acquire essential oil composition. The concentration and compositions of key flavour compounds like anethole, estragole and fenchone which impart fennel's characteristic liquorice-like taste, reach their highest levels at specific maturity stages,

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making the timing of harvest essential for culinary quality (Peyvast *et al*., 16). Recent studies have further highlighted that optimal maturity at harvest is critical for maximizing the antioxidant content, which is important for both nutritional benefits and extended shelf life (Kapoor and Aslam, 10). Exact maturity indices further to ensure desirable texture and visual appearance during storage and transport, thereby enhancing its marketability (Brahmi *et al*., 6). Seed yield plant^{-1} and 1000-seed weight progressively increased from immature to mature periods and delayed harvests can result in seeds on the primary umbel shattering, deteriorating and splitting. Therefore, a thorough understanding of these indices is essential for producing high-quality chewing-type fennel seeds that meet consumer expectations and industry standards.

The present study investigated the effect of harvesting seed umbels at different maturity stages on sensory attributes, seed yield, nutritional, antioxidant and oil compositions under field conditions.

MATERIALS AND METHODS

The current field experiment was conducted at the Indian Council of Agricultural Research - National Research Centre on Seed Spices (ICAR-NRCSS), Ajmer (Rajasthan), which is located in the Northwest of India (26.3661°N, 74.5933°E). Seeds of Ajmer Fennel-1 (AF-1) variety released from the ICAR-NRCSS, Ajmer, Rajasthan, India were sown in the field on 17th October of each year 2019, 2020 and 2021. The size of the plot was (10 × 6 m^2) and spacing (Row to row, plant to plant) was kept at 50 × 30 m^2. As recommended, half dose of nitrogen *i.e*. 25 kg N ha^{-1} and a full dose of phosphorus *i.e.* 25 kg P_2O_5 ha^{-1} were applied at the time of sowing and the remaining half dose of nitrogen was top-dressed in two equal split doses at 1-month interval. Thirty umbels of each (main, primary and secondary) order umbel were tagged as and when flowers were about to open. Umbels were harvested at six stages in five days intervals after the anthesis *viz*. 25 days after anthesis (132 DAS), 30 days after anthesis (137 DAS), 35 days after anthesis (142 DAS), 40 days after anthesis (147 DAS), 45 days after anthesis (153 DAS) and 50 days after anthesis (158 DAS) in each year. The anthesis occurred for 107 days, and the umbels were dried in the shed and then the seeds were separated and stored in paper bags at room temperature until the quality analysis of seeds. Individual umbels (king, primary, secondary) were used to measure seed colour. Mixed umbel seeds were used to estimate yield, nutritional, antioxidant assay, oil, and composition. A panel of eight technical and semi-technical judgements used a numerical scoring approach based on a nine-point hedonic scale to evaluate the visual appearance, flavor, aroma, texture, taste, fiberlessness, and overall acceptability of the seeds harvested at each stage (Dawodu *et al*., 8). A calibrated hand-held digital colourimeter Konika Minolta was used to measure the seed colour of the main, primary, and secondary umbels of fennel that were harvested at different intervals. The results were expressed as L* (lightness; 0 = black, 100 = white), a* (−a = greenness, +a = redness), and b* (−b = blueness, +b = yellowness). Each record was an average of measurements made on each seed sample. A standard white tile (L*= 96.82; a*= -0.02; b*= 2.04, enlighten condition C, 6774 K) was used to calibrate the colourimeter. The following equations were used to compute the various colourindices: hue: tan -1 (b*/a*)2, chroma: (a*2 + b*2) 0.5, and colour index (CI):2000 × a*/L*x (a*2+b*2)0.5 (Noreen *et al*., 14).

The colour difference ΔE (Delta E) is calculated based on where the seed's color readings are indicated by L*, a*, and b*.

$$\Delta E^* = \sqrt{(L_o^* - L^*)^2 + (a_o^* - a^*)^2 + (b_o^* - b^*)^2}$$

Five plants in all were tagged and entire plants umbels at different stages. The seeds of the different umbels were mixed, and after the seeds were properly dried in the shed. The yield of each year was calculated, and the mean yield of all the years (2018–19 to 2020–2021) was presented (kg ha^{-1}). The moisture content of freshly harvested fennel seeds was determined using the oven-drying method. Total Soluble Solids (TSS) were calculated using a portable refractometer (Atago PAL-1) (AOAC, 5). A standard micro-Kjeldahl method was used to determine the total nitrogen concentration and crude protein content (N × 6.25). The total seed phosphorus concentration was determined using the colourimetric vanado molybdate method, while the total potassium concentration was determined using flame photometry (Alcántar and Sandoval, 3) whereas crude fiber content was estimated as per AOAC (5).

Thirty grams of each treatment were hydro-distilled for 3 hours with a Clevenger apparatus to extract essential oils (Clevenger, 7). The seed extract was prepared with ethanol as the solvent (Ahmed *et al*., 2). TPC was determined using the Folin-Ciocalteu reagent (Manzoor *et al*., 12). The calibration standard was gallic acid, and the results were expressed in milligrams of equivalent gallic acid dry extract (mg GAE g^{-1}). The essential oils' potential to scavenge free DPPH radicals was determined using the DPPH test (Stanojevi´C *et al*., 19). Essential Oil (EO) Compositions were

determined by the vapor phase profiles of EOs and hydrosols (Hys) were characterized using a Perkin-Elmer Headspace (HS) Turbomatrix 40 autosampler connected to a GC-MS system. Quantification and identification of the chemical components were carried out using GC-FID and GC-MS techniques. The experiment was conducted using a Randomized Complete Block Design with six replications. In essential oil constituents at 25 DAA primary umbel and secondary umbels did not emerge hence value kept zero for statistical analysis. Likewise at 30 DAA secondary umbels did not emerge hence value was kept at zero for the analysis. The data obtained were subjected to analysis of variances, and significant differences between treatment means were evaluated using the DMRT test. Variance analysis was used to compare yield, nutrition, and oil composition parameters. Duncan's tests with R 3.3.2 were used to assess differences between observed data at a statistical significance level of $P < 0.05$. Using R 3.3.2's Facto Mine R, ade4, stats, ca, MASS, and Ex Position packages, principal component analysis (PCA) was used to assess associations between yield, nutritional, antioxidant, oil, and oil composition.

RESULTS AND DISCUSSION

Data on sensory evaluation is presented in Table 1. Results revealed that seeds harvested at 35 DAA, attained the highest overall acceptability score of 8.53, which corresponds with peak scores in appearance (8.70), flavour (8.50), texture (8.60), and taste (8.60), followed by 40 DAA (Table 2). Seed harvested at 35 DAA found the highest overall acceptability score over seed harvested at 50 DAA. It remained statistically at par with seed harvested at 40, 45, 30 and 25 DAA. At 45 DAA, the overall acceptability score decreased to 8.22 (Table 1). The 50 DAA stage showed the lowest overall acceptability score of 7.95, with a score in fiberlessness (7.50) and appearance (7.70).

In seed chromatic attributes, primary umbel seeds harvested at 35 DAA and 40 DAA had the highest lightness (L*) values, 47.53 and 47.45, respectively, while king umbel seeds at 50 DAA had the lowest L* value of 26.93. The (a*) values ranged from -1.65 in king umbel seeds at 50 DAA to -5.16 in secondary umbel seeds at 50 DAA. The highest b* value was in primary umbel seeds at 30 DAA (21.42), while king umbel seeds at 35 DAA had the lowest b* value (11.76). Primary umbel seeds at 45 DAA had the highest Chroma (22.14), and king umbel seeds at 50 DAA had the (CI) (0.59) and Delta E (62.24). Primary umbel seeds at 45 DAA had the highest Hue value (101.7), while secondary umbel seeds at 50 DAA had the lowest Hue value (71.4), indicating significant color variation across harvesting stages. King umbel seeds at 35 DAA had Chroma (12.22) and CI (0.27) values. Significant differences in seed color across umbel types and harvest stages were observed. King umbel seeds at 50 DAA had the lowest lightness (L*), while primary umbel seeds at 45 DAA showed the most intense colouration with the highest Delta E, Color Intensity (CI), and Chroma values. Seed color is a crucial quality factor, and harvesting at 35 DAA is recommended to meet consumer preferences for chewing fennel.

In the 2018-19 seasons, seed yield ranged from 755 kg ha^{-1} at 25 DAA to 1190 kg ha^{-1} at 50 DAA, with a significant rising trend observed each year (Table 4). This trend continued in the 2019-20 season, where seed yield increased from 761.79 kg ha^{-1} at 25 DAA to 1422.6 kg ha^{-1} at 50 DAA. The 2020-21 season showed similar results, with seed yield progressing from 809.68 kg ha^{-1} at 25 DAA to 1435.48 kg ha^{-1} at 50 DAA. In this study seed yield in fennel significantly increased with delayed harvest across the 2018-2021 seasons, culminating in a substantial yield enhancement at 50

Table 1. Sensory evaluation of fennel seed harvested at different stages after anthesis.

Harvesting stages	Appearance	Flavour	Aroma	Texture	Taste	Fiber lessness	Overall acceptability
25DAA	7.9 c	7.8 b	7.8 c	7.3 d	8.1 bc	8.9 a	7.97 ab
30DAA	8.1 bc	8.1 ab	8 bc	7.8 c	8.2 bc	8.7 ab	8.15 ab
35DAA	8.7 a	8.5 a	8.2 abc	8.6 a	8.6 a	8.6 ab	8.53 a
40DAA	8.5 ab	8.3 ab	8.4 ab	8.4 ab	8.4 ab	8.4 b	8.4 ab
45DAA	8.1 bc	8.2 ab	8.5 ab	8.3 ab	8 c	7.9 c	8.22 ab
50DAA	7.7 c	7.9 b	8.6 a	8.1 bc	7.9 c	7.5 c	7.95 b
CV (%)	1.88	2.365	2.139	1.719	1.46	2.096	2.433
P value	p<0.001	0.012	0.002	p<0.001	p<0.001	p<0.001	0.029

DAA: Days after anthesis, CV: Coefficient of variation, ptr: probability of treatment

Table 2. Changes in fennel seed colour attributes of different umbels harvested at different days after anthesis.

Treatment	*L**	*a**	*b**	Hue angle	Chroma	CI	ΔE
King umbel (25 DAA)	46.44 a	-4.34i	19.98 b	101.3 a	20.42 b	0.44 c	54.64 f
King umbel (30 DAA)	36.07 c	-4.19h	20.13 b	101.9 a	20.54 b	0.57 a	55.64 cdef
Primary umbel (30 DAA)	42.56 b	-3.98fg	21.42 a	101.7 a	22.14 a	0.52 b	54.28 f
King umbel (35 DAA)	45.26 a	-3.58e	11.76 j	98.2 a	12.22 g	0.27 e	60.17 ab
Primary umbel (35 DAA)	47.53 a	-3.51e	20.48 ab	100.8 a	21.35 ab	0.45 c	55.08 def
King umbel (40 DAA)	34.48 cd	-3.14c	15.55 ghi	80.1 b	15.92 e	0.46 c	59.35 abc
Primary umbel (40 DAA)	47.45 a	-3.88f	18.77 cd	101 a	19.19 c	0.4 d	55.71 cdef
Secondary Umbel (40 DAA)	32.92 de	-2.15b	14.59 i	80.8 b	14.71 f	0.45 c	61 a
King umbel (45 DAA)	30.01 f	-3.12c	17.1 ef	80.8 b	17.53 d	0.58 a	59.54 ab
Primary umbel (45 DAA)	42.81 b	-2.16b	16.08 fg	81.8 b	16.37 e	0.38 d	58.74 abcde
Secondary Umbel (45 DAA)	42.45 b	-3.35d	18.12 de	100.5 a	18.9 c	0.45 c	56.61 bcdef
King umbel (50 DAA)	26.93 g	-1.65a	15.89 gh	84.2 b	15.95 e	0.59 a	62.24 a
Primary umbel (50 DAA)	46.19 a	-4.02g	19.76 bc	101.2 a	20.44 b	0.44 c	55.04 ef
Secondary umbel (50 DAA)	31.42 ef	-5.16j	14.97 hi	71.4 c	16.28 e	0.52 b	58.78 abcd
CV(%)	1.931	-2.071	2.089	2.042	2.049	2.31	2.154
P value	p<0.001	p<0.001	p<0.001	p<0.001	p<0.001	p<0.001	p<0.001

DAA: Days after anthesis, CV: Coefficient of variation, ptr: probability of treatment

DAA. This variation in maturity also adds complexity to decisions regarding optimal yield and quality. This trend aligns with previous research demonstrating that delayed harvesting optimizes seed maturation and biomass accumulation, thereby contributing to increased yield. Early harvest (25 DAA) resulted in a considerably lower seed yield due to prevalent seed immaturity, especially in secondary and tertiary umbels. Although early harvest often yielded higher net returns, the overall yield was significantly compromised (Özel *et al*., 15; Moosavi, 13).

The highest total oil content was recorded at 25 DAA in the first two years (4.5% in 2018-19 and 4.7% in 2019-20), while in the third year (2020-21), the peak total oil content of 4.82% was observed at 30 DAA (Table 3). Conversely, the lowest total oil content at 50 DAA was 2.89% (2018-19), 2.47% (2019-20), and 2.52% (2020-21). Essential oil content also decreased with delayed harvesting, with the highest values at 25 DAA being 2.55% (2018-19), 2.61% (2019-20), and 2.55% (2020-21), and the lowest at 50 DAA being 2.19% (2018-19), 2.14% (2019-20), and 2.16% (2020-21). Total oil (TO) and essential oil (EO) content exhibited a progressive increase with advancing harvest stages, suggesting that extended maturation periods facilitate enhanced

Table 3. Variation in yield, total oil content and essential oil of fennel seeds harvested at different stages (Mean of three years).

Harvesting stages	Yield (kg ha^{-1})			Total oil (%)			EO (%)		
	2018-19	2019-20	2020-21	2018-19	2019-20	2020-21	2018-19	2019-20	2020-21
25 DAA	755 f	761.79f	809.68d	4.5a	4.7a	4.78a	2.55a	2.61a	2.63a
30 DAA	850 e	854.16e	855.48d	4.45a	4.63a	4.82a	2.53ab	2.53ab	2.55a
35 DAA	995 d	1010.5d	1018.3c	4.4a	4.57a	4.44b	2.42ab	2.45bc	2.48ab
40 DAA	1100 c	1174.4c	1166.94b	3.59b	3.99b	4.05c	2.38b	2.38cd	2.39bc
45 DAA	1130b	1241.5b	1249.14b	3.27c	3.19c	3.155d	2.21c	2.29d	2.27cd
50 DAA	1190 a	1422.6a	1435.48a	2.89d	2.47d	2.52e	2.19c	2.14e	2.16d
CV (%)	1.015	1.912	2.684	2.001	1.966	2.004	2.276	1.581	2.258
P value	p<0.001	p<0.001	p<0.001	p<0.001	p<0.001	p<0.001	p<0.001	p<0.001	p<0.001

DAA: Days after anthesis, CV: Coefficient of variation, ptr: probability of treatment, EO: Essential oil

Table 4. Changes in moisture, TSS and nutritional quality parameters of the seeds harvested at different intervals.

Stage	MC	TSS	CF	CP	N	P	K
25 DAA	74.51 a	24.6 b	12 f	21.41 a	3.44 a	0.378 d	1.99 a
30 DAA	73.5 a	25.63 ab	13.96 e	21.52 a	3.38 a	0.377 d	1.28 c
35 DAA	65.46 b	26.33 a	17.26 d	21.39 a	3.32 a	0.395 d	1.35 bc
40 DAA	58.51 c	21.32 c	19.59 c	21.47 a	3.3 a	0.454 c	1.39 b
45 DAA	45.9 d	18.21 d	23.46 b	20.89 a	3.29 a	0.485 b	1.39 b
50 DAA	32.61 e	13.06 e	28.68 a	20.58 a	3.25 a	0.581 a	1.42 b
CV(%)	2.018	2.575	1.739	2.064	2.552	2.081	1.94
P value	p<0.001	p<0.001	p<0.001	0.123	0.171	p<0.001	p<0.001

DAA: Days after anthesis, CV: Coefficient of variation, ptr: probability of treatment, MC: Moisture content, TSS: Total soluble solids, CF: Crude fibre, CP: Crude protein, N: Nitrogen, P: Phosphorus, K: Potas

oil accumulation. Peak TO and EO levels were consistently observed at 50 DAA, significantly surpassing those at 25 DAA. These findings are consistent with earlier research, which showed a positive correlation between delayed harvesting and enhanced oil synthesis and accumulation in seeds (Ravid *et al*., 18).

The mean values of moisture content showed a significant decrease across the stages from 25 to 50 DAA (Table 4). Starting at 74.51% at 25 DAA and reached the lowest value at 50 DAA (32.61%). Seed moisture content (MC) significantly decreased from 25 to 50 DAA, reflecting typical seed maturation patterns. The highest TSS value was observed at 35 DAA (26.33), which was significantly higher compared to 25 DAA (24.6), 40 DAA (21.32), 45 DAA (18.21), and 50 DAA (13.06). A marked decline in TSS was recorded at later stages, with values of 18.21 at 45 DAA and 13.06 at 50 DAA (Table 4). The high TSS contributes to the sweetness of fennel seeds, which is a key factor in consumer preference for seeds used for chewing. Crude fiber (CF) at 25 DAA, was 12, which progressively increased to 13.96 at 30 DAA, 17.26 at 35 DAA, 19.59 at 40 DAA, 23.46 at 45 DAA, and 28.68 at 50 DAA (Table 5). The mean and crude protein (CP) values were relatively stable, ranging from 20.58 to 21.52. Specifically, CP was measured at 21.41 at 25 days after application (DAA), 21.52 at 30 DAA, 21.39 at 35 DAA, 21.47 at 40 DAA, 20.89 at 45 DAA, and 20.58 at 50 DAA. Crude fiber content increased with seed maturity, peaking at 50 DAA and significantly higher than at 25 DAA. This increase in fiber negatively affected seed texture and consumer acceptability. Therefore, fennel seeds harvested between 30 and 35 DAA were found optimal for chewing purposes. Harvesting beyond this period led to poorer seed quality due to undesirable color changes and a fiber content rise to around 24%. Crude protein and seed nitrogen levels remained stable throughout, while K and P content decreased until 35 DAA before increasing again at 40-50 DAA. These results are consistent with previous research, highlighting the nutritional benefits of seeds harvested at 35-40 DAA.

Total phenol content at 25 DAA, was at its lowest (12.5 mg GAE g^{-1}) (Fig. 1). This content increased steadily with each subsequent harvesting stage, rising to 14.5 mg GAE g^{-1} at 30 DAA, 16.5 mg GAE g^{-1} at 35 DAA, and 18.5 mg GAE g^{-1} at 40 DAA, with the maximum increase observed between 25 and 40 DAA. The phenol content continued to rise, reaching 20.5 mg GAE g^{-1} at 45 DAA and peaking at 21.5 mg GAE g^{-1} at 50 DAA.

At 25 DAA, SEDPPH content was the lowest (2.1 units). This value increased progressively, reaching 2.7 units at 30 DAA, 3.2 units at 35 DAA, and 3.8 units at 40 DAA (Fig. 2). The most pronounced increase in SEDPH content occurred between 45 DAA (4.6)

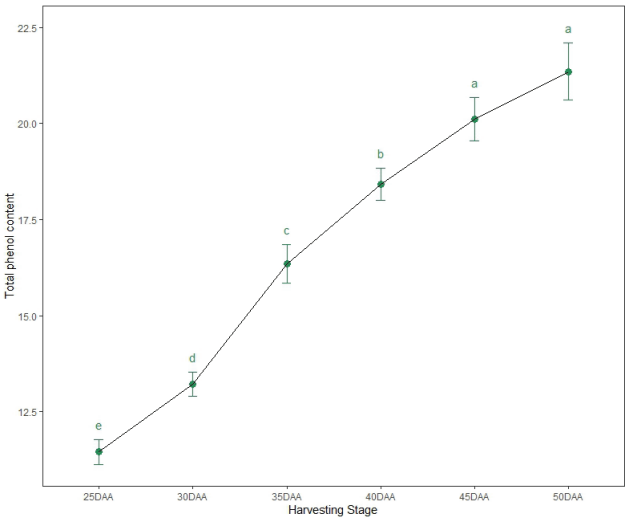

Fig. 1. Variation in total phenol content of seeds harvested at different intervals.

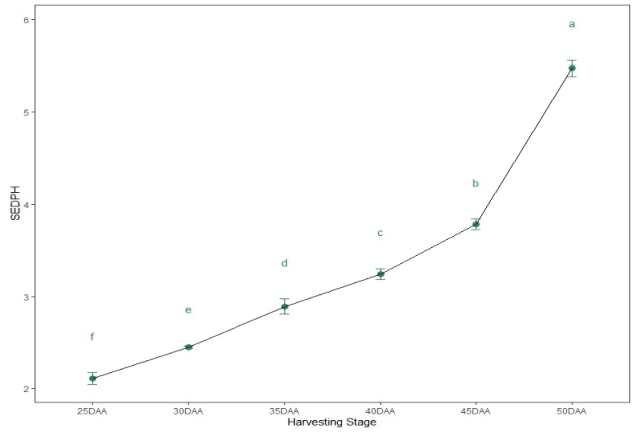

Fig. 2. Variation in seed extract 2,2-diphenyl-1-picrylhydrazyl of seeds harvested at different intervals.

and 50 DAA (5.9). The final stage, 50 DAA, had the highest SEDPH content, significantly different from all previous harvesting stages (Fig. 3). Initially, EODPPH was 15.5 at 25 (DAA) afterwards values increased progressively, reaching a maximum of 35.5 at 50 DAA. The EODPPH values were 15.5 at 25 DAA, 18.6 at 30 DAA, 21.2 at 35 DAA, 25.4 at 40 DAA, 30.3 at 45 DAA, and 35.5 at 50 DAA. Phenolic compounds, known for their antioxidant properties, are essential in plants. Phenolic compounds accumulated progressively from 25 to 50 DAA. Ethanol extracts consistently showed higher antioxidant activity than essential oils, with both improving as harvest progressed. These results align with previous research on the antioxidant potential of fennel seed extracts and essential oils (Ahmed *et al*., 2; Anwar *et al*., 4). The study highlights that the antioxidant capacity of fennel seed extracts and essential oils varies with harvest timing, allowing for optimization based on desired antioxidant levels.

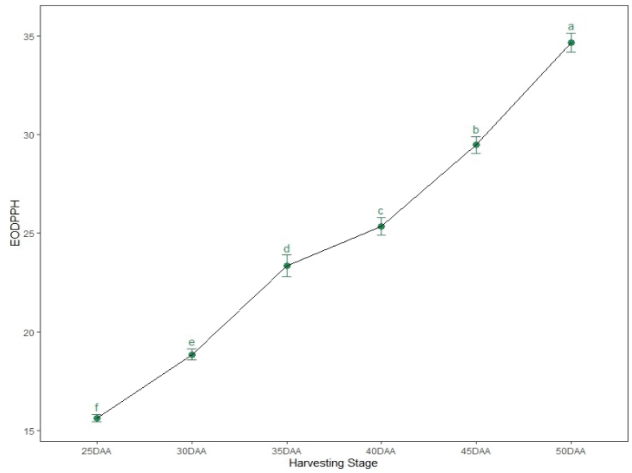

Fig. 3. Variation in essential oil 2,2-diphenyl-1-picrylhydrazyl of seeds harvested at different intervals.

Table 5. Umbel wise essential oil constituents of the seeds harvested at different intervals.

Stage	K(p)	Pr(p)	S(p)	K(f)	Pr(f)	S(f)	K(e)	Pr(e)	S (e)	K(ta)	Pr(ta)	S(ta)	K(l)	Pr(l)	S(l)
25 DAA	3.71 a	0 e	0 b	9.18 a	0 b	0 d	29.49 c	0 f	0 d	23.42 c	0 f	0 d	18.38 a	0 d	0 d
30 DAA	2.46 d	2.48 a	0 b	9.05 a	4.72ab	0 d	29.86 bc	37.71 c	0 d	32.56 a	24.43 d	0 d	10.41 d	15.67 a	0 d
35 DAA	2.59 c	2.09 c	1.96 a	6.33 c	8.17 a	9.157 a	31.16 abc	26.6 e	29.033 c	31.96 a	38.46 a	37.043a	13.09 c	7.44 c	7.83 c
40 DAA	2.26 e	1.67 d	1.97 a	8.19 b	7.63 a	7.537 b	31.52 ab	34.18 d	33.813 b	32.26 a	33.29 b	35.603b	8.55 e	13.89 b	9.45 b
45 DAA	2.88 b	2.32 b	2.05 a	8.94 a	7.17 a	6.273 c	32.95 a	44 a	40.733 a	29.24 b	20.1 e	26.063 c	17.4 b	15.94 a	15.7 a
50 DAA	2.17 e	1.63 d	2.06 a	8.82 a	7.14 a	6.3 c	32.03 a	40.32 b	40.91 a	23.14 c	25.84 c	26.587 c	8.5 e	14.07 b	16.033 a
CV (%)	1.53	1.879	3.38	2.432	29.15	2.153	2.172	1.825	1.935	1.495	2.063	1.637	1.367	2.283	2.097
P value	p<0.001	p<0.001	p<0.001	p<0.001	0.001	p<0.001	p<0.001	p<0.001	p<0.001	p<0.001	p<0.001	p<0.001	p<0.001	p<0.001	p<0.001

DAA: Days after anthesis, CV: Coefficient of variation, ptr: probability of treatment, K: King umbel, Pr: Primary umbel, S: Secondary umbel, p:α-pinene, f: fenchone, e: estragole, ta: trans-anethole, l: limonene

The effects of different harvesting stages (25, 30, 35, 40, 45, and 50 DAA) and types of umbels were observed on the important constituents of essential oil and the results are presented in Table 5. In king umbel, the α-pinene content was highest at 25 DAA, with a mean value of 3.71, and lowest at 50 DAA, with a mean of 2.17. Particularly α-pinene content for king umbel was 3.71 at 25 DAA, 2.46 at 30 DAA, 2.59 at 35 DAA, 2.26 at 40 DAA, 2.88 at 45 DAA, and 2.17 at 50 DAA. In the primary umbel, α-pinene content varied significantly, peaking at 30 DAA with a mean of 2.48. The mean α-pinene values for the primary umbel were 2.48 at 30 DAA, 2.09 at 35 DAA, 1.67 at 40 DAA, 2.32 at 45 DAA, and 1.63 at 50 DAA. For the secondary umbel, α-pinene content was recorded highest at 50 DAA (mean of 2.06). Fenchone content in king umbel seeds remained relatively high across harvesting stages, peaking at 9.18% at 25 DAA and slightly declining to 8.82% at 50 DAA. In primary umbel seeds, fenchone content significantly increased to 8.17% at 35 DAA before decreasing at later stages. Secondary umbel seeds showed a similar trend, with the highest content of 9.16% at 35 DAA, which was notably higher than at other stages. Estragole content in king umbel increased significantly from 29.49 at 25DAA to 32.95 at 45DAA, afterwards decreasing to 32.03 at 50 DAA. The primary umbel seeds showed an increase trend from 37.71 at 30 DAA to 44 at 45 DAA. The Estragole content in primary umbel seeds remained stable until 35 DAA but then increased significantly at 45 DAA (40.73). In king umbel seeds Trans- anethole content showed a significant increase from 23.42 at 25 DAA to 32.56 at 30 DAA, continuing high levels through subsequent stages. Primary umbel seeds exhibited a peak at 35 DAA (38.46), followed by a slight decrease at 40 DAA and 45 DAA, before stabilizing at 50 DAA. Trans-anethole content in secondary umbel seeds remained low until 35 DAA, where it peaked at 37.04, then gradually declined. The α-limonene content varied significantly across harvesting stages. In king umbel seeds, it peaked at 18.38% at 25 DAA, decreased to 17.40% at 45 DAA, and then fell to 8.50% at 50 DAA. For primary umbel seeds, α-limonene increased sharply to 15.67% at 30 DAA and remained high in later stages. The highest α-limonene content in secondary umbel seeds was recorded at 16.03% at 50 DAA. The essential oil composition of different umbels (king, primary, secondary) and harvesting stages revealed distinct trends in major constituents like α-pinene, fenchone, estragole, trans-anethole, and limonene. Trans-anethole, a primary component in fennel, increased from 45 to 50 DAA but is less desirable for market purposes. Optimal levels were found at 30 and 35 DAA. Methyl chavicol (estragole), another major component, ranged from 72.34 to 88.67% and increased with umbel age (El-Gamal and Ahmed, 9). Variations in essential oil quality are attributed to chemotypes, harvesting stages, drying methods, and environmental factors (El-Gamal and Ahmed, 9). These insights will help optimize harvest timing for key compounds like trans-anethole and fenchone, improving fennel quality to meet specific market demands

According to the scree plot analysis, the first two components account for maximum variance with eigenvalues of 14.2 and 3.5, respectively (Fig. 4a). The eigenvalues decrease significantly to 0.9, 0.4, 0.1, and 0 after these two components, illustrating that the remaining components have minimal impact on the total variance. Principal Component Analysis (PCA) revealed distinct patterns in yield and quality characteristics across developmental stages (25 DAA to 50 DAA) (Fig. 4b). The first principal component (PC1), explaining 74.5% of the variance, primarily reflected early-stage factors like seed extract DPPH (SEDPPH), chlorophyll content (CF), total phenolic content (TPC), and estragole from the primary umbel. PC2, accounting for 18.2% of the variance, was associated with intermediate-stage variables such as TA, TSS, and CP. Stages from 25 DAA to 45 DAA clustered together, suggesting similar yield and quality profiles, while the 50 DAA

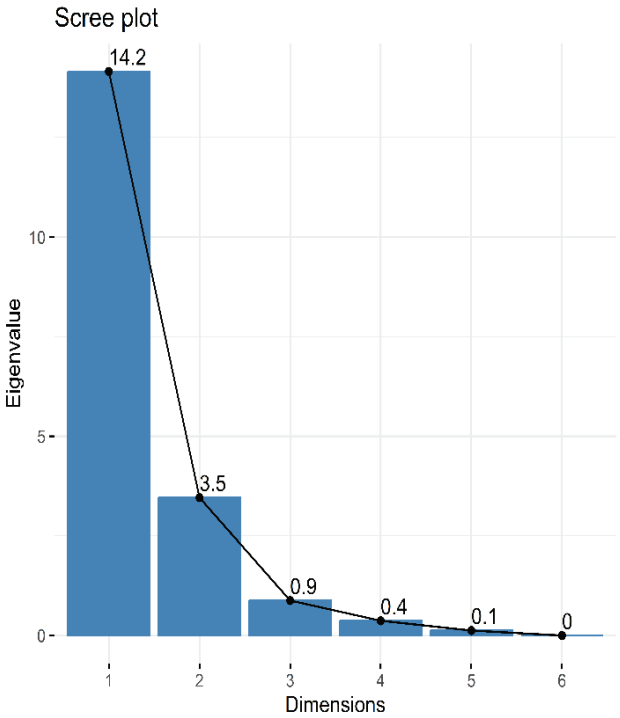

Fig. 4a. Scree plot yield and quality attributes of seed harvested at different stages.

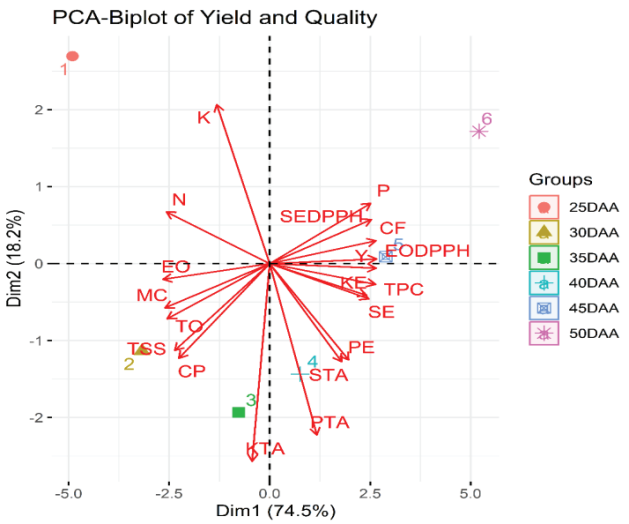

Fig. 4b. Principal component analysis of yield and quality attributes of seed harvested at different stages.

stage was distinctly separate, indicating substantial developmental changes. These findings provide actionable insights for optimizing crop management practices, from harvesting timing to tailored stage-specific interventions, ultimately leading to improved yield and quality.

The study found that harvesting fennel seeds at 35-40 days after anthesis achieves the best quality, including sensory properties, color, and nutritional content. Delaying harvest increases yield but lowers quality factors like fiber content and seed color. Essential oil composition also varies with harvest time and umbel type. Future research should focus on understanding fennel genetics and improving cultivation practices to enhance seed quality and yield.

AUTHORS' CONTRIBUTIONS

Writing - original draft, Formal analysis, Software, Data curation (SL); Investigation, Writing – review & editing, Supervision, Validation (GL); Writing – review & editing, Formal analysis, Conceptualization, Investigation (SNS). Methodology, Investigation, Writing – review & editing (MKM); Conceptualization, Validation, Resources (CKJ); Conceptualization, Investigation, Resources (MC).

DECLARATION

No potential conflict of interest was reported by the author(s).

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