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ORIGINAL PAPER

Hussein E. Osman and Atallah Abo Hassan

Phenotypic Diversity and Characterization of Jojoba Populations Established in Western Saudi Arabia

Abstract: Phenotypic characterization of a jojoba population of 5165 plants established in western Saudi Arabia revealed that 52.8% of the population were males, 46.4% were females and 0.8% were of unknown sex 54 months from planting. Among the male plants, 34.3% were early flowering and 65.7% were late flowering, whereas among females 46.9 and 53.10% were recorded as early and late flowering respectively. Among the male plants, 19.8% were abundant pollen producers and only 0.22% had a prostrate growth habit. Among the female plants, 5.13% had a cluster bearing habit (i.e. 3 fruits/node), 14.23% had fruits at every node and 9.72% had a high number of fruits per plant. Plant heights in the range 70–185cm, crown diameters in the range of 65-200 cm, internode lengths in the range of 1.4-5.1 cm, seed yield per plant in the range of 0-1418g, oil or wax content in the range of 34.9-56.4% and protein content in the range of 9.5 to 49.5% were recorded in the course of three years of the study. These ranges are comparable to those reported in other parts of the world. Plant height, crown diameter and internode length were negatively correlated (P = 0. 01) to one another. Wax content was negatively correlated ($P \leq 0.05$) toplant height. The coefficient of determination ($R^2 = 0.111$) indicated a low contribution of these traits in the total variability associated with seed yield, indicating the importance of directly selecting high yielding plants in yield improvement programs. Thus it is concluded that jojoba can be introduced as a commercial crop in Al-Medinah area. Additional work will be needed to select improved jojoba types for future plantations in Saudi Arabia.

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التباين المظهري و التوصيف العام لمجموعة نباتات الهوهوبا
بالمنطقة الغربية ، المملكة العربية السعودية

المستخلص : أوضح التوصيف المظهري لمجموعة الهوهوبا المستزرعة بالمنطقة الغربية المكونة من 5165 نباتا أن نسبة النباتات الذكور بالمجموعة قد وصلت إلى 52.8٪ بينما كانت نسبة الإناث 46.4٪ والنباتات الغير معروفة الجنس 0.8٪ . أما داخل مجموعة الذكور فقد وصلت نسبة النباتات المبكرة التزهير إلى 34.3٪ والمتأخرة إلى 65.7٪ بينما وصلت نسبة النباتات المبكرة داخل مجموعة الإناث إلى 46.9٪ والمتأخرة إلى 53.1٪ كذلك وصلت نسبة النباتات ذات الإنتاجية العالية من حبوب اللقاح داخل مجموعة الذكور إلى 91.8٪ بينما وصلت نسبة النباتات المفترشة للأرض إلى 0.12٪ . أما بين الإناث فقد حملت 5.1٪ اكثر من ثمرة في العقدة الواحدة و14.2٪ حملت ثمارا على جميع العقد و9.7٪ حملت شجيرتها عدداً كبيراً من الثمار . أما المتوسطات العامة للصفات المورفولجية فقد كانت 70 – 185 سم لطول النبات ، 70 – 200 سم لقطرة التاج ، 1 – 5.1 سم لطول السلامية ، صفر – 1418جم لوزن البذور للشجيرة ومن 34.9٪ إلى 60٪ لمحتوى الشمع و9.5 إلى 49.5٪ لمحتوى البروتين بالبذور خلال سنوات الدراسة ، وقد كانت هذه المعدلات مشابهة لما أظهرته الدراسات السابقة في أجزاء أخرى من العالم .

أظهرت الدراسة وجود ارتباطات إيجابية (P< 0.01) بين طول الشجيرة وقطر التاج وطول السلامية وارتباطا سلبيا (P< 0.05) بين محتوى البذور من الشمع وطول الشجيرة . كما أوضح معامل التحديد (R^2) تدني مشاركة الصفات التي شملتها الدراسة في التباين المظهري المرتبط بوزن المحصول مما يشير إلى أهمية الانتخاب المباشر للشجيرات ذات الإنتاجية العالية في برامج التربية لشجيرة الهوهوبا . وقد خلصت الدراسة إلى إمكانية إدخال الهوهوبا كمحصول تجاري لمنطقة المدينة المنورة وإلى أهمية إجراء دراسات إضافية لإدخالها تجاريا في مناطق أخرى من المملكة العربية السعودية .

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Hussein E. Osman and Atallah Abo Hassan
Faculty of Meteorology,
Environment and Arid Land Agriculture,
King Abdulaziz University,
P.O. Box 9034, Jeddah 21413,
Saudi Arabia
Tel:(9662) 6952371
Fax:(9662) 6952364

Introduction

Jojoba (*Simmondsia chinesis* (Link) Schneider), a dioecious plant (i.e. having males and females in different plants), is a new industrial crop that is attracting attention in many semi-arid parts of the world. Its seeds contain an appreciable amount of liquid wax (50%) that is needed to fill the gap created by the termination of sperm oil production (Brown *et al.* 1996). Consequently, worldwide seed production from commercial plantations is projected to amount to 9800 metric tons (Brown *et al.* 1996). Its ability to tolerate drought allows the shrub to produce a crop with significantly less water than is necessary for traditional crops (Al-Ani *et al.* 1972).

Efforts to produce genetically superior strains of jojoba have already started in several research institutions and it is commercially grown in the southern United States (Nelson, 1996), Mexico (Ayerza, 1996), Australia (Dunstone, 1996) and Palestine (Benzioni *et al.* 1996). As the case is with all perennial plants, progress will not be realized until several years go by. The most important yield components in jojoba include large seed, high oil content, flowers at every node, more than one seed per node in clusters, early flowering to escape frost in cool climates, precocious seed production starting before the fifth year and upright growth habit. Selection of low dormancy types for tropical areas and deep dormancy types for winter frost areas as suggested by Benzioni and Dunstone (1986) is also important.

The combination of all of the desirable traits in one superior variety requires time and dedicated research followed by years of testing. On the other hand, development of cultivars having some of these desirable traits could be achieved in a relatively short time through vegetative propagation. Palzkill already released three colonial cultivars of jojoba at the University of Arizona (Palzkill *et al.* 1989).

In the absence of an appropriate cultivar, jojoba growers around the world have been using one or more of the following options in establishing their plantations: (i) non-selected seedlings; (ii) selected seedlings; (iii) non-characterized female cuttings; and (iv) characterized cuttings (Brown and Palzkill, 1990). No doubt the use of non-characterized stock will result in lower yields initially, but it provides the wide genetic base needed for selecting desirable cuttings. At present, jojoba clones yielding up to 4 tons of seeds/ha are under commercial plantation elsewhere (Forti and Elharar, 1990).

Improper selection for an area that is prone to frost, has salt problems or has chilling conditions inappropriate for a cultivar can result in total failure of planting. This, according to Palzkill (1996), can only be avoided by conducting yield-testing trials at each intended planting site. According to Palzkill (1996), genetically adapted cultivars can be developed for areas that receive little or no chilling. In this respect, cultivars that do not seem to require chilling were identified in Mombassa, Kenya, and Arizona. This study was, therefore, undertaken to assess the performance and extent of phenotypic diversity in a jojoba population established from a diverse seed stock introduced from Arizona, U.S.A. in order to identify a high yielding jojoba plant type to be used in future plantations in western Saudi Arabia.

Materials and Methods

The experimental site, where the jojoba population was established, is located along the Makkah-Madinah Monawarah highway (Lat. 24° N and Long. 39° 36` E). The soil at the experimental site is sandy loam and the irrigation water was non-saline. The field consisted of 39 rows of flowering jojoba plants. Rows were spaced 4 m apart and each row was 175 m long. Plants within each row were spaced 1 to 1.5 m apart. Thus, an overall area of 2.73 ha supporting a plant population of 5165 plants made up this jojoba field. In the course of the study, the plants were frequently irrigated (monthly), and weeded once or twice a year, but they received no fertilizer. They were generally very healthy and were, therefore, not sprayed or treated against insects or diseases. Meteorological data taken at the experimental site is shown in Table 1. Data recorded in the first year of the study (1993) included percentage of males, females and sex-undetermined plants (i.e. those having no flower buds). The percentages of early and late flowering plants, and of upright and prostrate plants within each sex group were also determined. Within each female group, the percentages of plants having a relatively high number of fruiting branches, a single flower per every fruiting node, a single flower per every other node and clusters (i.e. 3 or more flowers) per node were also determined. The percentage of male plants having a relatively high number of flower clusters (i.e. abundant pollen producers) was also determined. In addition to these traits, plant height, internode length, crown width, seed yield per plant, wax and protein content of seeds (when present) were also measured for each of 600 plants randomly

Table 1: Absolute seasonal ranges of temperature and relative humidity at the experimental site in the period 21/6/93 to 20/12/96

	1993 / 1994		1994 / 1995		1995 / 1996	
Season	Temp. (°C)	R.H. (%)	Temp. (°C)	R.H. (%)	Temp. (°C)	R.H. (%)
Winter (W)	-	13-98	4-34	20-100	6-36	9-100
Spring (Sp)	-	14-96	7-44	6-95	12-45	19-100
Summer (S)	20-45	13-95	16-48	9-100	17-47	22-100
Fall (F)	9-42	6-98	8-40	20-100	11-42	13-98

tagged from the 30 middle jojoba rows at harvest.

In 1994 and 1995 each of the 30 middle rows of the population was divided into two sub-populations. Ten female plants were randomly tagged per each sub-population, harvested in bulk and used to determine yield per plant, protein and wax content of seeds. Wax content was determined by the ether extract method using an automatic extraction unit (Soxtect System HT 1043, Tecator), whereas an automatic analyzer (Kjeltec Auto Analyser 1030, Tecator)) was used for protein (nitrogen) determination.

Results and Discussion

Sex Related Traits

Sex ratio

Out of the 5165 plants surveyed, 2726 plants were males, 2396 were females and 43 were of unclassified sex (Table 2). Percentages of the three sex groups were respectively 52.8, 46.4 and 0.8%. Yermanos (1979) assessed the sex ratio in a jojoba plantation established at Riverside, California, USA, and reported a male to female ratio of 54.3 to 45.7%. This ratio, according to him, represents a significant deviation from a 1:1 ratio in favor of the males.

Early and late flowering plants

Out of 2726 male plants in the jojoba population, 935 (34.3%) were early flowering and 1791 (65.7%) were late flowering (Table 2). In the female group 1124 (46.9%) were early flowering and 1272 (53.1%) were late flowering. Yermanos (1979) showed that in a population of 4045 plants, 2751 (68%) were early and 1294 (32%) were late. His data also showed that among the early types, 60% were males and 40% were females.

Prostrate and upright plant type

Data in Table 2 indicate that of the whole population only 8 plants (0.15%) were prostrate. Out of these, 6 (0.12%) were males and 2 (0.08%) were females. Thus, the upright plant type constituted almost the whole jojoba population in Al-Medinah area. No doubt, this is a desirable trait that helps in pollen dissemination and distribution from males and facilitates mechanical harvesting and/or manual picking of seeds.

Abundant pollen producers

Production of abundant pollen by an individual male is a desirable trait as it ensures adequate pollination to take place and consequently a high percentage of fruit set in jojoba female plants. Out of the whole male population, 541 plants (19.8%) were abundant pollen producers (Table 2).

Table 2: Summary of the distribution of genetically inherited traits charecterizing jojoba population established in Al-Madinah area (1993)

	1993 / 1994		1994 / 1995		1995 / 1996	
Season	Temp. (°C)	R.H. (%)	Temp. (°C)	R.H. (%)	Temp. (°C)	R.H. (%)
Winter (W)	-	13-98	4-34	20-100	6-36	9-100
Spring (Sp)	-	14-96	7-44	6-95	12-45	19-100
Summer (S)	20-45	13-95	16-48	9-100	17-47	22-100
Fall (F)	9-42	6-98	8-40	20-100	11-42	13-98

Plate 1a: Jojoba fruits: clustered vs. single bearing habit

Plate 1b: Jojoba fruits: every node bearing habit

Mode of fruit bearing

Jojoba plants bear their fruit either in clusters (three or more fruits per node) or as single fruits per node. Within the latter group, some of the fruits are borne in every node of the fruiting branch while in other plant types, they are borne in every other node of the fruiting plant. Among the three fruiting modes, cluster and every node bearing habits were reported to be desirable and were likely to contribute to high seed yield (Yermanos, 1982). Data presented in Table 2 indicated that of the whole female population, 123 plants (5.1%) had a cluster bearing habit (Plate 1a), while 341 plants (14.2%) had fruits in every node (Plate 1b). Visual observation indicated that out of the whole female population, 233 (9.7%) appeared to have a high number of fruiting branches and/or a high number of fruits per shrub.

Seed Yield and its Related Traits

Plant height

Plant height ranged from 70 to 185 cm with an overall average of 112.95 ± 0.72 cm (Table 3). The distribution of these estimates around their mean is shown in Fig.1a. The c.v., being 15.56%, indicated a moderate range of phenotypic variability and consequently a limited chance of improvement in plant height through mass selection.

Crown Diameter

As shown in Table 3, crown diameter ranged from 65-200cm with an overall mean of 137.39 ± 1.04 cm. The distribution of these estimates around their mean is shown in Fig.1b. The c.v., being 18.61%, indicated a moderate range of phenotypic variability and consequently a limited scope for genetic gain through mass selection.

Table 3: Overall performance (vegetative growth) of a 600 jojoba plant population in season 1993/94

	Plant height (cm)	Crown diameter (cm)	Internode length* (cm)
Range	70-185	65-200	7.0-25.5
Mean	112.95	137.39	13.26
S.E.±	0.72	1.04	0.13
C.V.	15.56	18.61	23.02

Internode length

As shown in Table 3, length of a five internode branchlet ranged from 7 to 25.5 cm with an overall average of 13.26 ± 0.13 cm . The distribution of these measurements around their mean is shown in Fig.1c. The c.v., being 23.02%, indicated a moderate chance of improvement in this trait through mass selection. As jojoba fruits are borne at nodal segments, selection of plant types with shorter internodes and a higher number of nodes may improve seed yields in jojoba. However, for any particular genotype, the percentage of nodes bearing flower buds was reported to be affected by temperature (Dunstone, 1982).

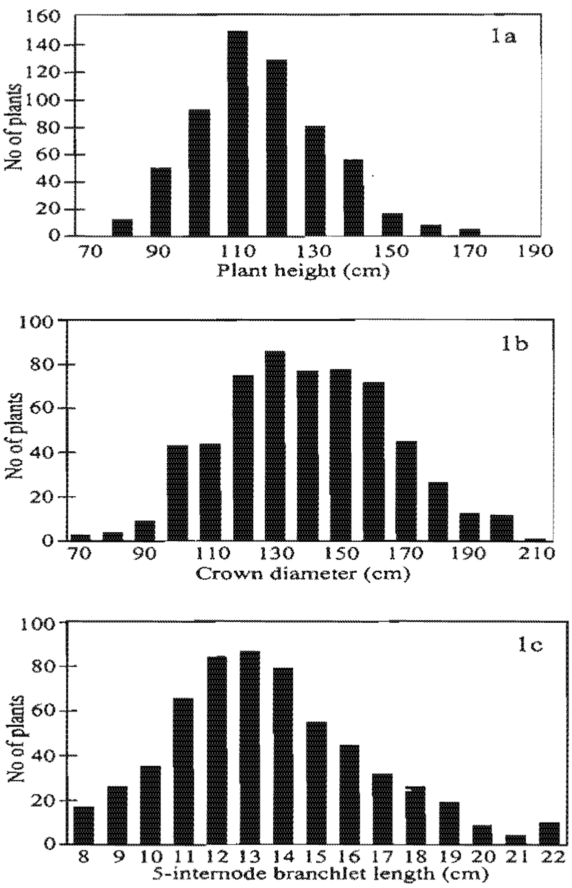

Fig 1: Plant height (a), crown diameter (b), and internode length (c)

Wax (oil) content of seeds

Oil content in jojoba seeds harvested from 407 individual plants in 1993 ranged from 34.9 to 56.4%, being almost symmetrically distributed around the mean (42.97 ± 0.16%) as shown in Fig.2b. The c.v., being 7.70%, indicated a narrow range of phenotypic variability for the trait and consequently a limited chance for its improvement through mass selection. Oil percentages in the range of 44 to 58% (Yermanos, 1982) and 49.4 to 56.2% (Ayerza, 1996) have been reported in the literature. Oil content in seeds was reported varying with plant age (Yermanos, 1975), and between genotypes (Yermanos and Duncan, 1976). Oil content of seeds was reported to be stable under a wide range of temperatures (18/13 to 33/28°C), whereas its quality was adversely affected at lower temperatures (15/13°C) or higher temperature (36/31°C) ranges (Dunstone et al., 1985). In the present study, wax content recorded in 1995 was significantly lower (P ± 0.01) than that recorded in 1994 (Table 4), indicating that environmental stresses that prevailed in 1995 or those accumulated by the plant up to this age had adversely affected oil content.

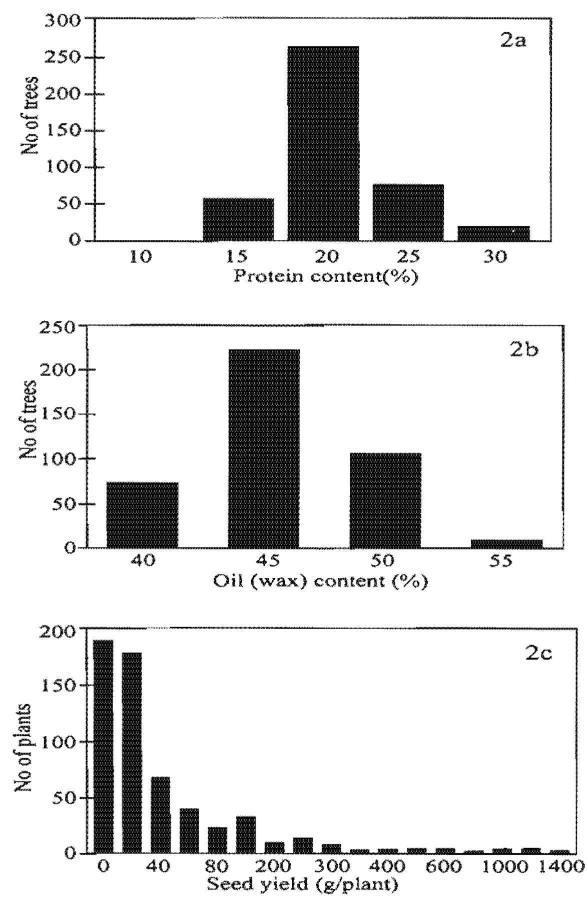

Fig 2: Protein content (a), oil content (b), and seed yield (c)

Protein content

Protein content in the seeds of 400 plants assessed in 1993 ranged from 9.5 to 49.5% with an overall average of 17.77 ± 0.15% (Table 4). The frequency distribution of these percentages around their mean is shown in Fig.2b. The c. v., being 20.79%, indicated a moderate chance of improving

Table 4: Seed yield, wax and protein contents of seeds in a jojoba population in seasons 1993/94 - 1995/96

	Seed yield** (g/tree)			Wax content** (%)			Protein content* (%)		
Season	92/93	93/94	94/95	92/93	93/94	94/95	92/93	93/94	94/95
Range	0.0-1417.5	135.1-1232.5	86.0-1200.0	34.9-56.4	39.9-54.0	37.7-46.3	9.5-49.5	13.4-19.9	14.3-23.0
Mean	57.58	475.4	611.3	42.88	44.59	42.6	17.78	16.91	17.77
S.E.±	6.28	27.1	33.0	0.16	0.16	0.24	0.18	0.17	0.22
C.V. (%)	267.2	44.1	41.8	7.7	9.3	4.4	20.79	7.8	9.6

this trait through mass selection. Protein content in jojoba meal was reported to average about 30% (Yermanos, 1982). Average estimates of protein content in 1994 and 1995, being 16.91 and 17.70% (Table 4), showed that this trait, unlike oil content, was relatively more stable (P ± 0.05) with plant age and/or environmental changes.

Seed yield

The distribution of seed yield per plant for the 600 plants tagged in 1993 ranged from 0 to 1417.5 g with an overall average of 57.58 ± 6.28 g and a c.v. of 267.2% (Table 4). The distribution of the yields around their mean is shown in Fig.2c. It is evident from this data that 32% of the plants did not contribute to seed yield and 49% had yielded less than 60 g seed/plant at this stage. Only eleven plants out of 600 had yielded more than 1000g/plant out of which three excelled at 1400 g seed/plant (Fig.2c). In Mombassa, an equatorial region, where chilling requirements are unlikely to be fulfilled, data taken in a 3-year period showed that of 964 mature jojoba plants 58% produced less than 50g seed/plant and 38% produced no seed. Among the remaining plants, two averaged more than 1.5 kg over the three years period, and one of the plants produced 3.2kg in one season (Palzkill, 1996). Yields in the range of 0 to 500 gm/plant in five year old plants and up to 2000 g/plant in seven year old plants were reported in California (Yermanos, 1982). Yields in the range of 148 to 705 g/plant were reported by Ayerza (1996) for three year old plants, whereas those for 16, 17 and 18 year old plants were reported to be 0.95, 1.3 and 3.2 t/ha for the respective ages (Milthrope and Yee, 1996). In Israel (Benzioni *et al.* 1996), yields in the range of 3.1 to 6.1 kg/plant were harvested from 12 year old jojoba clones. Differences in seed yield were associated with those in branching index, node length, flower index, growth habit and chilling requirement among the clones. In the present study, yields (averaged over 10 plants) of up to 1233 g (1994) and 1200 g (1995) were harvested from 66 and 72-month-old plants (Table 4). Seed yield averaged over the 600 plants was 57.58,475.4 and 611.3 g /plant for the seasons 1993, 1994 and 1995, respectively. Apparently, continued vegetative growth and floral bud production as indicated by Yermanos (1982) results in relatively higher yields in subtropical areas than in relatively cooler areas.

Interrelationships

Simple correlation analysis (Table 5) showed that none of the studied traits was positively correlated to seed yield. Plant height was positively correlated to crown diameter and internode length and negatively to oil content (Table 5). Oil content was negatively correlated (P = 0.01) to plant height (Table 5), which was reported to be highly associated with plant age especially in subtropical areas (Yermanos, 1982). Although plants as tall as 5.0 m were observed, positive relationships between plant height and crown diameter, as in this study, were not established (Yermanos, 1982). Forti *et al.*, (1985) reported a negative relationship between seed yield and plant crown diameter. According to him, plants with narrow crowns yielded up to 4.2 kg of seed/plant, whereas in those with wide crowns, yields were limited to 1.2 kg/plant.

Partial regression analysis (Table 6) reveled that none of the studied traits had a significant contribution to seed yield. The coefficient of determination (R^2) showed that only 11.1% of the variability in seed yield could be attributed to its association with the five quantitative traits evaluated in this study (Table 6). Consequently, direct selection of individual plants will prove to be an effective

Table 5: Simple correlation coefficients between seed yield and related traits (1993/94)

	Plant Height	Crown Diameter	Internode Length	Wax Content	Protein Content
Crown diameter	0.554**				
Internode length	0.125*	0.194**			
Wax content	-0.154**	-0.094	-0.015		
Protein content	0.062	0.029	-0.063	0.004	
Seed yield	-0.079	-0.047	-0.007	0.086	-0.028

approach in seed yield improvement programs.

No doubt flower development is a prerequisite for seed production. If temperature conditions at a specific site interfere with flower development of a selected cultivar, it will likely not produce well (Palzkill, 1996). Dunstone (1980, 1982) and Benzioni and Dunstone (1986) have carefully documented the physiological necessity for jojoba flower buds of a period of chilling temperature to overcome dormancy. Without such chilling temperature, plants remain non-productive, even though they may be healthy and contain many flower buds. At 27/22°C to 36/31°C, jojoba produced only dormant flower buds, whereas 98 % of male clones broke dormancy at 15/10°C and 67% of female clones at 12/7°C. A wider diurnal range (up to 17°C) had no effect on this response (Dunstone, 1980). In tropical areas mean winter temperatures of 16.3°C were reported to induce higher seed yields than those reaching 19°C, whereas in temperate areas flowering rarely occurs outside the cool period of autumn and early spring (Benzioni and Dunstone, 1986). Preconditioning floral buds at 30/25°C, according to Dunstone (1982) caused a higher percentage of buds to break dormancy than that at either higher or lower temperatures. Other factors (e.g. water supply, age of the flowering bud, conditions prevailing during bud development, supply of nutrients and radiation level) were reported to be involved in breaking flower bud dormancy (Benzioni and Dunstone, 1986). Meteorological data recorded at the experimental site is shown in Table 1. At this site vegetative growth as observed by Osman *et al.* (1997) and consequently floral bud formation, as reported by Yermanos (1982) and Benzioni (1985), continued through out the year, as it requires no specific environmental conditions. Flowering (protrusion of the stigma or anthers) and fruiting were, however, observed in early winter, whereas fruit maturity continued through the spring and early summer.

Dunstone and Dawson (1983) reported a positive correlation (r = 0.96) between percentage of flowering and mean daily radiation in female, but not in male, clones. Dunstone and Dawson (1983), in contrast to Yermanos *et al.* (1979), indicated that flowering response in jojoba is insensitive to day length. As light radiation is not a limiting factor in subtropical areas, chilling temperatures, as indicated by Palzkill (1996) appeared to be more important in determining the flowering pattern in western Saudi Arabia.

It is thus evident from this study that the performance of jojoba in western Saudi Arabia is comparable to that in other parts of the world where the crop is commercially grown. Continued regional testing to select appropriate cultivars or clones for each location is needed. Consequently, commercial plantation of selected jojoba clones in Al-Medinah area, where this work was conducted, will prove to be a desirable practice in the future.

Table 6: Partial regression analysis of seed yield and related traits (1993/94)

	Coefficient	S.E.±	t-value	p-value
Plant height x_1	-0.6611	0.626	-1.056	0.291
Crown diameter x_2	-0.0257	0.430	-0.060	0.952
Internode length x_3	0.0558	3.04	-0.018	0.985
Protein content x_4	4.2437	2.830	1.499	0.135
Oil content x_5	-1.1877	2.467	-0.481	0.630

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