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EFFECT OF DEFICIT IRRIGATION ON PHYSICAL AND MECHANICAL PROPERTIES OF DATE FRUIT

Dear * Dr. Ahmed M. Hassan, ** Dr. Mohamed S. Omran,
*** Dr. Abdelgader M. Saleh.

* Assoc. Prof., Ag. Eng. Dept., Faculty of Agriculture, Cairo University. ** Assoc. Prof., Ag. Eng. Dept., Faculty of Agriculture, Cairo University. *** Assist. Prof., Ag. Eng. Dept., Faculty of Agriculture, Omar Elmukhtar University.



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ABSTRACT

The aim of this research work was to determine the effects of deficit irrigation on the physical and elasticity properties of date fruits (*Phoenix dactylifera*, cv *Talees*) during three stages of ripening (khalal, rutab and tamar) for three years (2010-2012). Four irrigation treatments were studied: (ET₁: 1 time potential crop evapotranspiration (ET_c), ET₂: 0.85 ET_c, ET₃: 0.75 ET_c and 0.65 ET_c, ET₄). The physical properties included the date mass, volume, dimensions, moisture content, bulk density, flesh thickness, projected area, and elasticity of fruits, also kernel mass and volume. The elasticity properties of fruit included Young's modulus of elasticity (E), firmness coefficient (FC), bioyield stress point (σ_b), bioyield strain point (ϵ_b), rupture stress point (σ_r), rupture strain point (ϵ_r) and rupture energy (RE). The results showed that Ripening stages for date fruit showed a significant effect on mechanical properties with ET₄. With different deficit irrigation treatments, the values of E, FC, σ_b , σ_r and RE were decreased from khalal to rutab stage then increasing with tamar stage.

Keywords: Deficit irrigation, Date palm, modulus, bioyield, and stress.

تأثير النقص المائي على الخواص الطبيعية والميكانيكية لثمار البلح

* د. احمد محروس حسن، ** د. محمد سيد عمران، *** د. عبد القادر محمد صالح

(* أستاذ الهندسة الزراعية المساعد – كلية الزراعة – جامعة القاهرة – مصر. ** أستاذ الهندسة الزراعية المساعد – كلية الزراعة – جامعة القاهرة – مصر. *** محاضر الهندسة الزراعية - كلية الزراعة – جامعة عمر المختار – البيضاء – ليبيا)

الملخص:

يهدف هذا البحث إلى تقدير الخواص الطبيعية والميكانيكية لثمار التمر (تاليس) أثناء مراحل النضج (خلال، رطب، تمر) تحت اربعة مستويات من الاحتياجات المائية المنزرعة في سبها بليبيا، لما تمثله هذه الخواص من أهمية في عمليات حصاد وتداول ثمار التمر في المراحل المختلفة للنضج، وبغرض المساهمة في تقليل الأضرار الميكانيكية التي تتعرض لها التمور خلال عملية النقل والتخزين من خلال التنبؤ بارتفاع عبوات قادرة على الحفاظ على الثمار من هذه الأضرار. وقد تم تقدير كل من الخواص البعدية للثمرة، سمك اللحم، المحتوى الرطوبي للثمرة، الكثافة الظاهرية للثمار، كتلة وحجم البذرة، وأيضاً خواص المرونة للثمرة مثل معامل "يانج" للمرونة، معامل الصلابة، وإجهاد الخضوع الحيوي، انفعال الخضوع الحيوي، إجهاد التحطم، انفعال التحطم، والطاقة اللازمة للتحطيم. وقد بينت الدراسة ما يلي:

1. توجد فروق معنوية بين مراحل نضج الثمرة في معظم الخصائص الطبيعية لمستويات المياه المختلفة.
2. توجد فروق معنوية بين مراحل نضج الثمرة في الخصائص الميكانيكية لسنف تاليس لمستويات المياه المختلفة: معامل يانج للمرونة ومعامل الصلابة وإجهاد الخضوع الحيوي وانفعال الخضوع الحيوي وإجهاد التحطم وانفعال التحطم والطاقة اللازمة للتحطيم.
3. تقل قيم الخواص الميكانيكية من مرحلة خلال إلى مرحلة الرطب ثم بعد ذلك تزيد من مرحلة الرطب إلى مرحلة التمر وذلك مع مستويات المياه المختلفة.
4. أقصى ارتفاع مأمون للعبوات كانت 267.12، 503.41، 557.64، 716.49 مم للسنف تاليس لمستويات المياه ET1، ET2، ET3، ET4 على الترتيب.

INTRODUCTION

Water plays a crucial role in determining the yield of processing tomato but it is likely that a water scarcity period will have to be faced in the near future. Water shortage and the increasing competition for water resources between agriculture and other sectors compel the adoption of irrigation strategies in semi-arid Mediterranean regions, which may allow saving irrigation water and still maintain satisfactory levels of production (*Costa et al., 2007*).

Date palm (*Phoenix dactylifera, L.*) is one of the most important horticultural crops rich in vitamins. Date production in the world is only confined to a small number of countries, most of them being the Arab countries. Date palm is the economic crop in Libya, where production was approximately 150 thousand tons (*Arab Agricultural Statistics Yearbook, 2009*).

In Libya date palms are distributed mainly in three areas: coastal, middle and southern districts. There are about (6) million date palm trees in Libya grown of about (400) cultivars.

The major cause of mechanical damage (bruising) is impact. Impact sensitivity of fruits and vegetables is defined as having components, namely bruise threshold and bruise resistance (*Bajema and Hyde, 1998*). Bruising in fruits and vegetables occurs when the produce rubs against each other, packaging containers, parts of processing equipment and the tree (*Altisent, 1991*).

Date fruits pass through several maturity stages, traditionally described by changes in color, texture and taste.

Several investigations have shown some of the chemical compositional changes that take place during maturation, including free sugars and tannins (*Myhara et al., 1999; Sawaya et al., 1983; Sawaya et al., 1982*). Green dates stage (kimri) are firm in texture with highest moisture and tannin contents. At the Khalaal stage, dates begin to lose moisture and form considerable quantities of sucrose. In the Rutab stage, the loss of moisture is accelerated, and the fruits become softer in texture, and sucrose is converted into sugars. Dates at Rutab stage are the most desirable since they are at their softest and sweetest states. In the final maturity stage (Tamr) the fruits contain the least amount of moisture and maintain a soft texture with a sweet taste. *Ismail et al., (2001)* studied the consumer preference for quality attributes of date (maturity of Tamr stage). Consumer gave weight on the acceptance as: high (color, appearance, and sweetness), medium (fruit size, flesh thickness, chewiness, and solubility).

Knowledge of the physical properties of date fruit is necessary for the design of post harvesting equipment such as cleaning, sorting, grading, kernel removing, and packing. The importance of dimensions is in determining the aperture size of machines, particularly in separation of materials as discussed by *Mohsenin (1986)*. These dimensions can be used in designing machine components and parameters.

Grading fruit, based on weight, reduces packing and handling costs and also provides suitable packing patterns (*Khoshnam et al., 2007*).

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Many studies have been reported on the physical and mechanical properties of fruits, such as bergamot (*Rafiee et al. , 2007*), coconut (*Terdwongworakul et al., 2009*), date fruit (*Jahorni et al., 2008*), kiwi fruit (*LoRESTANI and Tabatabaefar, 2006*), melon (*Emadi et al., 2009*), orange (*Khojastehnazhand et al., 2009*) and citrus fruits (*Omid et al., 2010*). *Akar and Aydin (2005)* evaluated some physical properties of gumbo fruit varieties as functions of moisture content. *Kashaninejad et al. (2006)* and *Awady and Sayed (1994)* determined some physical and aerodynamic properties of peanuts pistachio nuts and kernels as functions of moisture content in order to design processing equipment and facilities. *Ghonimy and Kassem. (2011)* reported that there are significant differences between different production zones of date fruits for each of fruit mass, flesh mass, fruit volume, fruit moisture content, fruit dimensions, flesh thickness, fruit projected area and elasticity of fruits.

Fecete (1994) found that the coefficient of elasticity for tomato and apple can be used to characterize the fruit firmness. *Cenkowski et al. (1995)* studied the effect of moisture sorption hysteresis on the mechanical behaviour of canola and showed that the modulus of elasticity of the product brought into equilibrium through adsorption was higher than that of the one obtained through desorption at the same moisture content. The other products whose mechanical properties have been studied include kiwi fruit (*Abbott and Massie, 1995*), apples (*Abbott and Lu, 1996*) and sea buckthorn berries (*Khazaei and Mann, 2004*). *Anazodo and Chikwendu (1983)* developed equations for the calculation of the Poisson's ratio and elastic modulus of circular bodies subjected to radial compression and *Dinrifo and Faborode (1993)* applied the Hertz's theory of contact stresses to cocoa pod deformation. *Anazodo and Norris (1981)* noted that the modulus of elasticity, crushing strength and modulus of toughness of corncob all decreased with moisture content.

The aim of this research was to investigate some physical and elastic properties for Talees date fruits during three stages of ripening (Khalaal, Rutab and Tamr) under four water levels to develop a technique that can predict the packing height to protect fruits from mechanical damage.

MATERIAL AND METHODS

1. Location, plant materials and sample preparation

The experiments were conducted during seasons 2010, 2011 and 2012. Physical and mechanical properties of date fruits (*Phoenix dactylifera*) were determined at three ripening stages. One variety (Talees) was selected from Sabha privet farm (located in the western south of Libya, 27° 02' 20" N and 14° 25' 35" E). Table (1) shows the average monthly climatic data (1962 – 1990) from January to December of the experimental area.

Four irrigation treatments were applied (ET₁: 1 time potential crop evapotranspiration (ET_c), ET₂: 0.9 ET_c, ET₃: 0.8 ET_c and 0.7 ET_c, ET₄). The Plot consists of 6 rows (48 x 48 m). Irrigation water was delivered via a trickle system. The emitters used in the trickle irrigation system were with flow rate of 8 L/hr, the trees were spaced at 8 m with 4 emitters per tree (16 mm in external diameter polyethylene tubes). For each treatment, 100

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date fruits were randomly selected at each ripening stage. Dates were sorted to discard the damaged fruits, and immediately kept for less than 24 hours in a cold storage at 5 °C.

Table (1): Climate data for Sabha (1962–1990)*

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T_{max}, °C	18.9	22.0	26.1	31.8	35.7	39.2	38.3	37.8	35.9	31.3	24.9	20.0
T_{min}, °C	4.5	6.8	10.6	15.9	20.1	23.6	23.0	22.9	21.3	16.9	10.7	5.7
rain, mm	1.1	0.8	0.5	0.5	0.3	0.5	0.0	0.0	0.4	2.1	0.9	1.1
relative humidity, (%)	42	37	31	22	27	27	32	30	27	29	38	40
sunshine, hours/month	260	252	269	275	304	341	375	361	295	284	258	252

* World Meteorological Organization

2. Determination of crop irrigation water requirement

The FAO Penman–Monteith method (*Allen et al., 1998*) was used to calculate the reference evapotranspiration ET_o in the CROPWAT Program. Crop water requirements (ET_c) over the growing season were determined from ET_o according to the following equation using crop coefficient K_c :

$$ET_c = K_c ET_o \dots\dots\dots(1)$$

Where ET_c is the crop water requirement, K_c is the crop coefficient and ET_o is the reference evapotranspiration. Since there was no rainfall during the experimental period, net irrigation requirement was taken to be equal to ET_c .

The total amounts of irrigation water applied in the irrigation levels in this study were 1839.1 mm in ET_1 , 1695.2 mm in ET_2 , 1531.7 mm in ET_3 and 1324.4 mm in ET_4 . The water requirement was determined for different months based on crop growth stages and climatic data.

3. Physical properties of date fruit

3.1. Date fruits dimensions (length and diameter)

All dimensions of date fruit and kernels were measured by Vernier calliper to an accuracy of 0.1 mm.

3.2. Date fruit moisture content

The moisture content was determined for the flesh of dates using AOAC procedures (*AOAC, 1995*) where the samples were dried at 70°C for 48 hours.

3.3. Mass and bulk density

The mass of date fruit was determined using a digital balance with an accuracy of 0.01 g. The bulk density of date fruits was calculated using equation (1) by determining the mass of the date and its volume.

$$D_b = \frac{m}{V} \quad (1)$$

Where;

D_b = The bulk density of date fruit, g/cm³;

m = Mass of date fruit, g;

V = Volume of date fruit, cm³.

4. Mechanical properties of date fruit

4.1. Compression test

The parallel-plate compressive test was carried out to determine the mechanical properties using a universal testing machine (Instron-1000 N)

Individual date fruits were uniaxially compressed at a cross-head speed of 0.5 mm/s to a total deformation 10 mm. A plate (diameter 7.5 cm) compressed a date flesh slab placed on a mounted fixed table. The contact surfaces were oriented parallel to the compression surfaces during loading (Fig. 1). A random 10 fruits sample of each cultivar at each ripening stage were taken for compression tests. All experiments were carried out at room temperature (23 °C).

The contact area between the parallel-plate disk surface and each tested fruit surface was determined experimentally. The plunger disk surface was covered with a white paper, followed by gently pressing the horizontally oriented upper longitudinal fruit surface in an ink stamp, and then allowing the plunger to contact the fruit surface. The resulting contact area traced on the white paper was scanned, and specially developed software that accurately estimates the scanned surface area was used to determine the contact area.

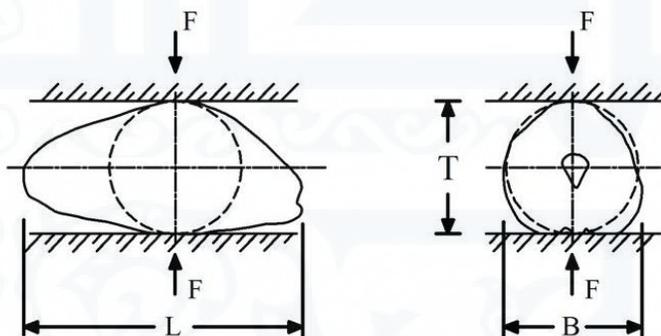


Fig. (1): Date fruit loaded between the two parallel plates

4.2. Elastic property of date fruit

A typical force-deformation curve (*Mohsenin 1986*) is shown in Figure (2). As it is shown, the force-deformation curve exhibited two peak points. The first peak corresponds to the yield point at which kernel damage was initiated. The second peak corresponds to the maximum compressive force.

For stress-strain tests, the following mechanical properties were calculated; the modulus of elasticity (E), firmness coefficient (FC), bioyield stress (σ_b), bioyield strain (ε_b), rupture stress (σ_r), rupture strain (ε_r) and rupture energy toughness (RE).

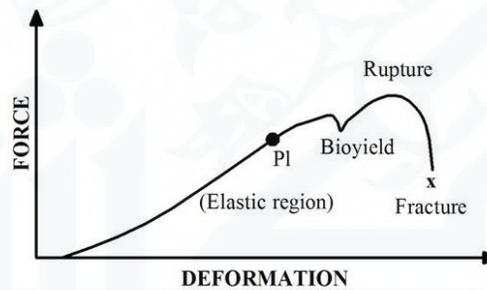


Fig. (2): A typical force-deformation plot for agricultural materials (*Mohsenin 1986*).

The Young's modulus of elasticity is a good measure of the elasticity of ideal materials. The behavior of ideal materials is described by the Hooke's law and the model of which is a spring without damper.

The Young's modulus of elasticity (E) for compressive stress is expressed by equation (2).

$$E = \frac{\sigma}{\varepsilon} \quad (2)$$

Where;

E = Young's modulus of elasticity, kPa;

σ = Compressive stress, kPa;

ε = Strain, mm/mm.

The strain was calculated by dividing the deformation of the fruit by the initial fruit average thickness.

$$\varepsilon = \frac{\Delta l}{l} \quad (3)$$

Where;

Δl = Variation in the thickness (deformation), mm;

l = Original thickness, mm.

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The average stress was calculated by dividing the force on one fruit by the projected area of the fruit as follows:

$$\sigma = \frac{F}{1000A_p} \quad (4)$$

Where;

F = force on one fruit, N,

A_p = Contact area of date fruit, mm².

Firmness coefficient (FC) is calculated as the average slope of force – deformation curve from zero to point of rupture or failure (*Shafiee et al., 2008*). FC was calculated by applying the following equation (5) :

$$FC = \frac{F}{\Delta l} \quad (5)$$

Toughness (RE) or mechanical energy or work required for rupture was determined by calculating the area under the force – deformation curve from the following equation (*Braga et al., 1999*):

$$RE = \frac{F_r D_r}{2} \quad (6)$$

Where;

RE = Toughness, J;

F_r = the rupture force, N;

D_r = the deformation at rupture point, m.

The area was measured by using a computer software program (AutoCAD), then, to relate the rupture energy to date fruit volume, it was divided it by date fruit volume.

5. Statistical analysis

Statistical analysis was carried out using a randomized complete block procedure of the MStat-c statistical package. LSD and Duncan multiple range comparison were used to identify means that were different at probabilities of 5 % or less (*Snedecor and Cochran 1976*).

6. Determination of the height of packing box

The force acting on stacks of fruit may be used to estimate the force acting on a date fruit at the bottom layer of a bulk bin. Figure (3) shows the force (F) acting on date fruit somewhere in stack. In this study, the date fruits are represented by cylinders of an average diameter (d) and a square arrangement which depends on their characteristic diameter and number of fruits.

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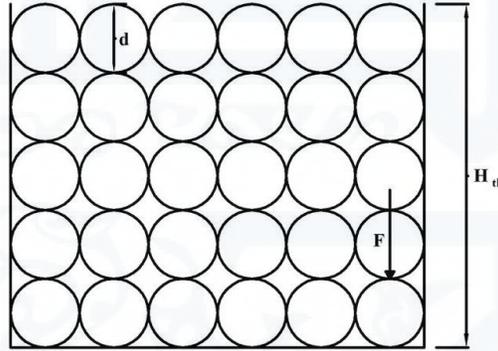


Fig. (3): An elevation view through the stack of date fruits in arrangement.

The following equations (7, 8, and 9) calculated the number of fruit of fruits above the bottom layer and consequently the height of the packing box.

$$F_{max} = n \cdot m \quad (7)$$

$$H_{th} = d \cdot (n + 1) \quad (8)$$

$$H_{act} = \frac{H_{th}}{S.F.} \quad (9)$$

Where:

F_{max} = Maximum allowable force on a date fruit at the bottom layer, N.

H_{th} = Maximum depth of fruit in box, (without mechanical damage),
mm.

H_{act} = Actual depth of fruit in box, mm.

n = Number of fruits above the last fruit at bottom layer.

m = Fruit weight, N.

d = Fruit diameter, mm.

$S.F.$ = Safety factor (≈ 1.5) as design factor to avoid any unexpected risk.

5.1. Determination of the contact stress

Heinrich Hertz (*Shigley et al., 2008*) proposed a solution for contact stress in two elastic isotropic bodies, such as the case of two cylinders (line contact) of the same material touching each other and attempted to find the magnitude of the maximum pressure. Figure (4) shows two cylinders of length l (the length of cylinder = fruit length) and diameters $d1$ and $d2$. The area of contact is a narrow rectangle of width $2b$ and length l , and the pressure distribution is elliptical.

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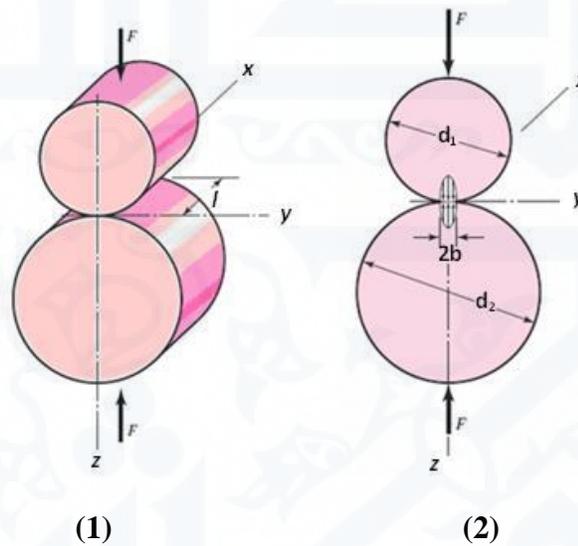


Fig. (4): Line contact of two cylinders: (1) Two circular cylinders held in contact by forces F uniformly distributed along cylinder length l . (2) Contact stress has an elliptical distribution across the contact zone width $2b$.

The half-width b is given by the equation (Shigley *et al.*, 2008):

$$b = \sqrt{\frac{2F}{\pi l} \frac{(1-\mu_1^2)/E_1 + (1-\mu_2^2)/E_2}{1/d_1 + 1/d_2}} \quad (10)$$

Where:

b = half of contact width, mm.

F = Acting force on the two cylinders, N.

l = contact length, mm.

E_1, E_2 = Modulus of elasticity for cylinders (1) and (2), Pa.

μ_1, μ_2 = Poisson ratio for cylinders (1) and (2), dimensionless.

d_1, d_2 = Diameter for cylinder (1) and (2), mm.

The maximum pressure (P_{max} , Pa) is called the Hertz (compressive) stress which occurs at the center and is given by following equation:

$$p_{max} = \frac{2F}{\pi b l} \quad (11)$$

RESULTS AND DISCUSSIONS

4.1. Physical characteristics of date fruits

Table (2) shows the average values of fruit mass, fruit volume, bulk density, fruit length, fruit diameter and fruit thickness. Minimum values of the mass (4.95 g) and length (21.84 mm) were found with ET₄ treatment, while the minimum values of diameter (17.5 mm), thickness (9.94 mm) and volume (4.27 cm³) were found with ET₁ treatment, but the minimum value of solid density (0.82 g/cm³) was found with ET₂. All the previous physical properties were found with Khelaal ripening stage except solid density was found with Tamr ripening stage. The maximum values of the mass (11.43 g) and length (37.2 mm) were found with ET₁ treatment and Rutab ripening stage, while the maximum values of width (20.89 mm) and solid density (1.16 g/cm³) were found with ET₄ treatment and with Tamr and Khelaal ripening stages, respectively, but the maximum values of thickness (11.86 mm) and volume (11.85 cm³) were found with ET₂ treatment and with Tamr ripening stage.

Table (2): Some average physical properties of date for different treatments.

Treats	Stage	Fruit mass, g	Flesh mass, g	Fruit volume, cm ³	Solid density, g/cm ³	Bulk density, g.cm ⁻³	Moisture content, %	Fruit length, mm	Fruit diameter, mm	Flesh thickness, mm
ET1	Khelaal	7.62 ^{bc}	3.98 ^c	7.00 ^c	1.09 ^a	0.61 ^b	71.65 ^a	27.3 ^{bcd}	17.5 ^b	9.94 ^{ab}
	Rutab	11.43 ^a	5.22 ^{ab}	10.80 ^{ab}	1.06 ^a	0.64 ^{ab}	58.64 ^{ab}	37.2 ^a	19.3 ^{ab}	11.7 ^a
	Tamr	10.94 ^{ab}	6.24 ^a	12.00 ^a	0.91 ^{ab}	0.67 ^a	22.67 ^c	34.9 ^a	19.9 ^a	11.4 ^a
ET2	Khelaal	7.32 ^{bc}	3.95 ^{bc}	6.90 ^c	1.06 ^a	0.62 ^{ab}	70.06 ^a	27.36 ^{bcd}	17.42 ^{ab}	10.29 ^{ab}
	Rutab	11.09 ^a	5.03 ^{ab}	10.77 ^b	1.03 ^{ab}	0.66 ^{ab}	57.21 ^{ab}	36.5 ^a	19.02 ^{ab}	11.34 ^a
	Tamr	9.74 ^{ab}	6.13 ^a	11.85 ^a	0.82 ^c	0.69 ^a	20.67 ^c	34.86 ^a	19.37 ^a	11.86 ^a
ET3	Khelaal	6.54 ^{bc}	3.21 ^c	6.33 ^{cd}	1.03 ^{ab}	0.67 ^a	69.32 ^a	24.36 ^{cd}	17.55 ^b	10.23 ^a
	Rutab	9.87 ^{ab}	5.02 ^{abc}	9.7 ^{bc}	1.02 ^{ab}	0.71 ^a	50.64 ^{ab}	33.21 ^a	19.01 ^{ab}	11.45 ^a
	Tamr	8.64 ^b	5.87 ^{ab}	10.21 ^{ab}	0.85 ^c	0.72 ^a	19.32 ^{cd}	31.69 ^{ab}	19.42 ^a	11.63 ^a
ET4	Khelaal	4.95 ^c	2.79 ^{cd}	4.27 ^d	1.16 ^a	0.75 ^a	58.64 ^{ab}	21.84 ^{cd}	17.92 ^{ab}	10.65 ^a
	Rutab	8.57 ^b	4.02 ^{bc}	7.99 ^c	1.07 ^a	0.75 ^a	43.25 ^b	30.2 ^{bc}	20.67 ^a	11.53 ^a
	Tamr	8.10 ^b	4.24 ^{bc}	7.68 ^c	1.05 ^a	0.78 ^a	17.47 ^{cd}	30.53 ^{bc}	20.89 ^a	11.68 ^a

(a) Mean values with different letters are significantly different (< 5% level).

The results show that the mass of date fruit decreased by decreasing crop water requirements. Same results trend was found for the length and volume. While the width and thickness increased by decreasing crop water requirements. The reason for these results is due to water stress decreasing the above-mentioned measurements.

Results showed that the fruit mass increased from Khalaal stage to Rutab stage, while decreased from Rutab to Tamr. Different trend was found with ET2, ET3, and ET4 treatments, where the date dimensions increased from Khalaal stage to Rutab stage, then increased from Rutab to Tamr. Data proved that the physical properties of date fruit were greatly influenced by ripening stage with all water levels.

For the four water levels, the statistical analysis (at 5% level) showed significant differences for most physical properties of date fruits during three stages of ripening (Khalaal, Rutab and Tamr).

4.2. Mechanical properties of date fruit

The mechanical properties of date fruit varieties at different ripening stages included modulus of elasticity (E), firmness coefficient (FC), bioyield stress (σ_b), bioyield strain (ε_b), rupture stress (σ_r), rupture strain (ε_r), and rupture energy (RE) as shown in table (3). Ripening stages for date fruit showed a significant effect on mechanical properties ($P < 0.01$).

2.1. Stress (σ) – Strain (ε) curve

Figure (5: a, b, c) shows the stress-strain curve of date palm (*Talees* variety) during different ripening stages under four different water levels. For the four water level treatments, the statistical analysis (at 5% level) showed significant differences for most elasticity properties of date fruits during three stages of ripening (Khalaal, Rutab and Tamr).

The elastic limits were (112.3, 42.4 and 51.9 kPa), (115.6, 40.9, and 50.8 kPa), (121.3, 43.6 and 53.4 kPa) and (127.2, 46.1, and 56.2 kPa) for ET1, ET2, ET3 and ET4 treatments, respectively. The results showed that the elastic limit decreased from Khalaal to Rutab stage, while increased from Rutab to Tamr. The reason may be due to the major changes which take place in the structural tissues during the on-going maturation process and change from Khalaal to Rutab to Tamr stage of maturity. The most significant changes are in sugar type which converts from sucrose to fructose and glucose as a result of enzymatic action during the maturation process. The changes in pectin by pectinase enzyme lead to softness in the date structure at the Rutab stage compared to the Khalaal stage despite the reduction in moisture content at the Rutab stage. Also the results showed that the elastic limit increased with decreasing water level.

Table (3): Some average mechanical properties of date for different treatments.

Treats	Stage	Elasticity	Firmness	Bioyield point		Rupture point		Rupture
		Modulus (kPa)	Coeff. (N/mm)	stress (kPa)	strain	stress (kPa)	strain	energy (MJ/m ³)

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ET1	Khelaal	1051.80 ^a	0.75 ^{ab}	277.3 ^{ab}	0.44 ^{ab}	442.35 ^a	0.56 ^a	0.1184 ^b
	Rutab	6.67 ^{de}	0.16 ^c	6.12 ^d	0.26 ^c	10.65 ^b	0.4 ^{ab}	0.0124 ^c
	Tamr	59.31 ^c	0.14 ^c	10.35 ^{cd}	0.21 ^{cd}	15.32 ^b	0.21 ^c	0.0213 ^c
ET2	Khelaal	894.22 ^{ab}	0.77 ^a	284.56 ^{ab}	0.48 ^{ab}	453.25 ^a	0.59 ^a	0.1268 ^b
	Rutab	4.32 ^{de}	0.15 ^c	7.24 ^d	0.31 ^{bc}	11.54 ^b	0.39 ^b	0.00486 ^c
	Tamr	55.67 ^c	0.15 ^c	10.36 ^{cd}	0.25 ^c	17.36 ^b	0.21 ^c	0.01158 ^c
ET3	Khelaal	824.56 ^{ab}	0.79 ^a	297.69 ^a	0.51 ^{ab}	472.32 ^a	0.58 ^a	0.21356 ^a
	Rutab	4.33 ^{de}	0.16 ^c	7.87 ^d	0.32 ^{bc}	12.00 ^b	0.41 ^{ab}	0.00865 ^c
	Tamr	55.01 ^c	0.15 ^c	11.64 ^{cd}	0.28 ^c	18.64 ^b	0.22 ^c	0.01195 ^c
ET4	Khelaal	784.81 ^{abc}	0.8 ^a	324.35 ^a	0.62 ^a	486.32 ^a	0.61 ^a	0.26033 ^a
	Rutab	4.29 ^{de}	0.16 ^c	8.69 ^d	0.38 ^{abc}	12.91 ^b	0.43 ^{ab}	0.0134 ^c
	Tamr	53.57 ^{cd}	0.17 ^c	17.84 ^{cd}	0.33 ^{bc}	21.37 ^b	0.24 ^c	0.01223 ^c

(a) Mean values with different letters are significantly different (< 5% level).

2.2. Modulus of elasticity (E)

The average values of Young's modulus of elasticity (E) for date fruits at different ripening stages and water levels are shown in table (3) and figure (6-a). It is clear that the modulus of elasticity (E) decreased from Khalaal to Rutab stage, while increased from Rutab to Tamr which was common trend for all water level treatments.

For ET1 treatment, the values of modulus of elasticity were 1051.8 kPa, 6.67 kPa and 59.31 kPa for Khalaal, Rutab and Tamr stages respectively. For ET2 treatment, the values of modulus of elasticity were 894.22 kPa, 4.32 kPa and 55.67 kPa for Khalaal, Rutab and Tamr stages respectively. For ET3 treatment, the values of E were 824.56 kPa, 4.33 kPa and 55.01 kPa for Khalaal, Rutab and Tamr stages respectively. For ET4 treatment, the values of E were 784.81 kPa, 4.29 kPa and 53.57 kPa for Khalaal, Rutab and Tamr stages respectively. The results showed that the values of modulus of elasticity decreased with decreasing water level

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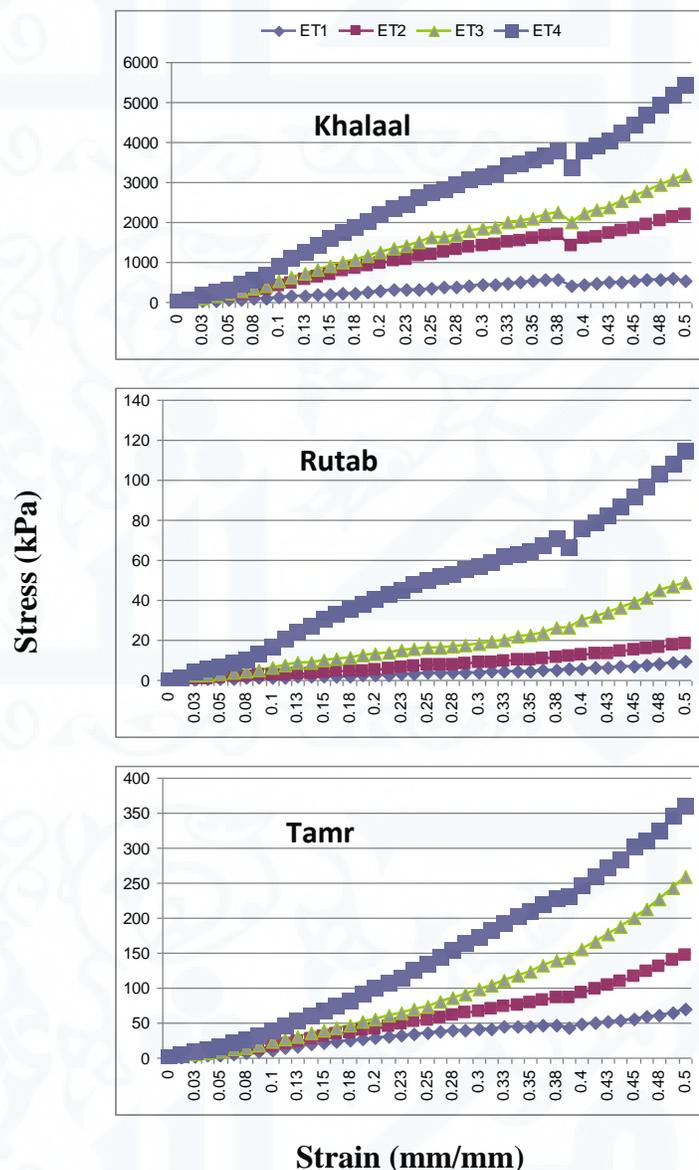


Fig. (5): Stress- strain curves of date fruit varieties at different ripening stages.

For the four water levels, the statistical analysis (at 5% level) showed significant differences for E of date fruits during the three stages of ripening (Khalaal, Rutab and Tamr).

2.3. Firmness Coefficient (FC)

The average values of firmness coefficient (FC) for date fruits at different ripening stages and water levels are shown in table (3) and figure (6-b). It is clear that the firmness coefficient (FC) decreased from Khalaal to Tamr stage, for all different water levels. Also the results showed that the values of FC increased with decreasing water level.

For ET1 treatment, the values of FC were 0.75, 0.16, and 0.14 N/mm for Khalaal, Rutab and Tamr stages, respectively. For ET2 treatment, the values of FC were 0.77, 0.15,

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and 0.15 N/mm for Khalaal, Rutab and Tamr stages respectively. For ET3 treatment, the values of FC were 0.79, 0.16, and 0.15 N/mm for Khalaal, Rutab and Tamr stages respectively. For ET4 treatment, the values of FC were 0.80, 0.16, and 0.17 N/mm for Khalaal, Rutab and Tamr stages respectively.

For the different water levels, the statistical analysis (at 5% level) showed significant differences for FC of date fruits during the three stages of ripening (Khalaal, Rutab and Tamr).

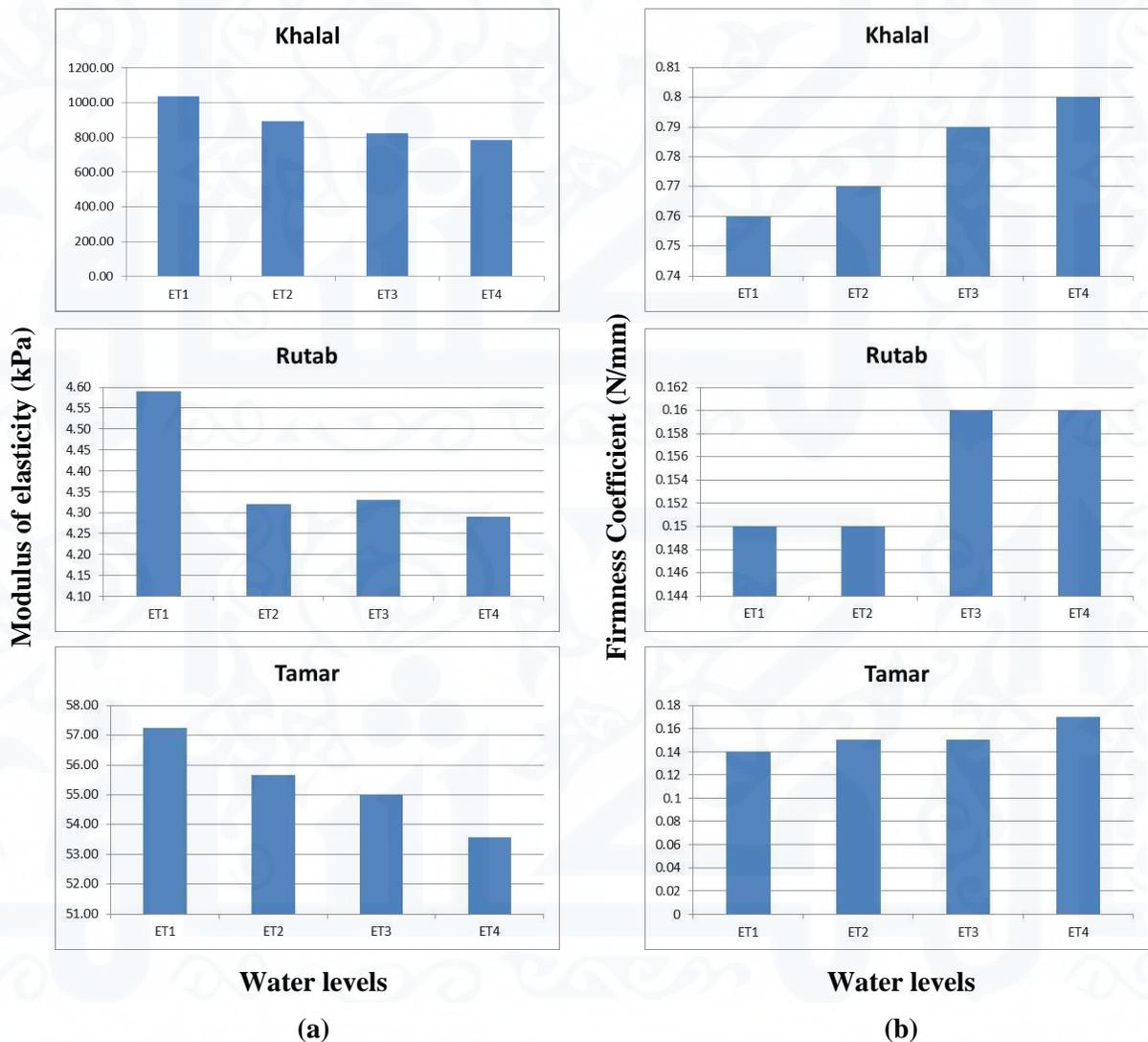


Fig. (6): Modulus of elasticity (E) and firmness coefficient (FC) for different water levels at different ripening stages of date fruit.

2.4. Bioyield stress (σ_b)

The average values of bioyield stress (σ_b) for date fruits at different ripening stage and water levels are shown in table (3) and figure (7-a). It is clear that the bioyield stress (σ_b) decreased from Khalaal to Rutab stage, while increased from Rutab to Tamr, with all water levels. In case of ET1 treatment, the values of (σ_b) were 277.3, 6.12, and 10.35 kPa for Khalaal, Rutab and Tamr stages respectively. In case of ET2 treatment, the values of (σ_b) were 284.56, 7.24, and 10.36 kPa for Khalaal, Rutab and Tamr stage respectively. In the case of ET3 treatment, the values of (σ_b) were 297.69, 7.87, and 11.64 kPa for Khalaal, Rutab and Tamr stages respectively. In the case of ET4 treatment, the values of (σ_b) were 324.35, 8.69, and 17.84 kPa for Khalaal, Rutab and Tamr stages respectively.

For the different water levels, the statistical analysis (at 5% level) showed significant differences for σ_b of date fruits during the three stages of ripening (Khalaal, Rutab and Tamr).

2.5. Bioyield strain (ϵ_b)

The average values of bioyield strain (ϵ_b) for date fruits at different ripening stages and water levels are shown in table (3). It is clear that the bioyield strain (ϵ_b) decreased from Khalaal to Tamr stage, with all different water level treatments.

In case of ET1 treatment, the values of ϵ_b were 0.44, 0.26, and 0.21 mm/mm for Khalaal, Rutab and Tamr stages, respectively. In case of ET2 treatment, the values of ϵ_b were 0.48, 0.31, and 0.25 mm/mm for Khalaal, Rutab and Tamr stages, respectively. In case of ET3 treatment, the values of ϵ_b were 0.51, 0.32, and 0.28 mm/mm for Khalaal, Rutab and Tamr stages, respectively. In case of ET4 treatment, the values of ϵ_b were 0.62, 0.38, and 0.33 mm/mm for Khalaal, Rutab and Tamr stages, respectively.

The results also showed that the values of bioyield strain (ϵ_b) increased with decreasing water level.

For the four water level treatments, the statistical analysis (at 5% level) showed significant differences for ϵ_b of date fruits during the three stages of ripening (Khalaal, Rutab and Tamr).

2.6. Rupture stress (σ_r)

The average values of rupture stress (σ_r) for date fruits at different ripening stages for the different water levels are shown in table (3) and figure (7-b). It is clear that the rupture stress (σ_r) decreased from Khalaal to Rutab stage, while increased from Rutab to Tamr, with all different water level.

In case of ET1 treatment, the values of σ_r were 442.35, 10.65, and 15.32 kPa for Khalaal, Rutab and Tamr stages, respectively. In case of ET2 treatment, the values of σ_r were 453.25, 11.54, and 17.36 kPa for Khalaal, Rutab and Tamr stages, respectively. In case of ET3 treatment, the values of σ_r were 472.32, 12, and 18.64 kPa for Khalaal, Rutab and Tamr stages, respectively. In case of ET4 treatment, the values of σ_r were 486.32, 12.91, and 21.37 kPa for Khalaal, Rutab and Tamr stages, respectively.

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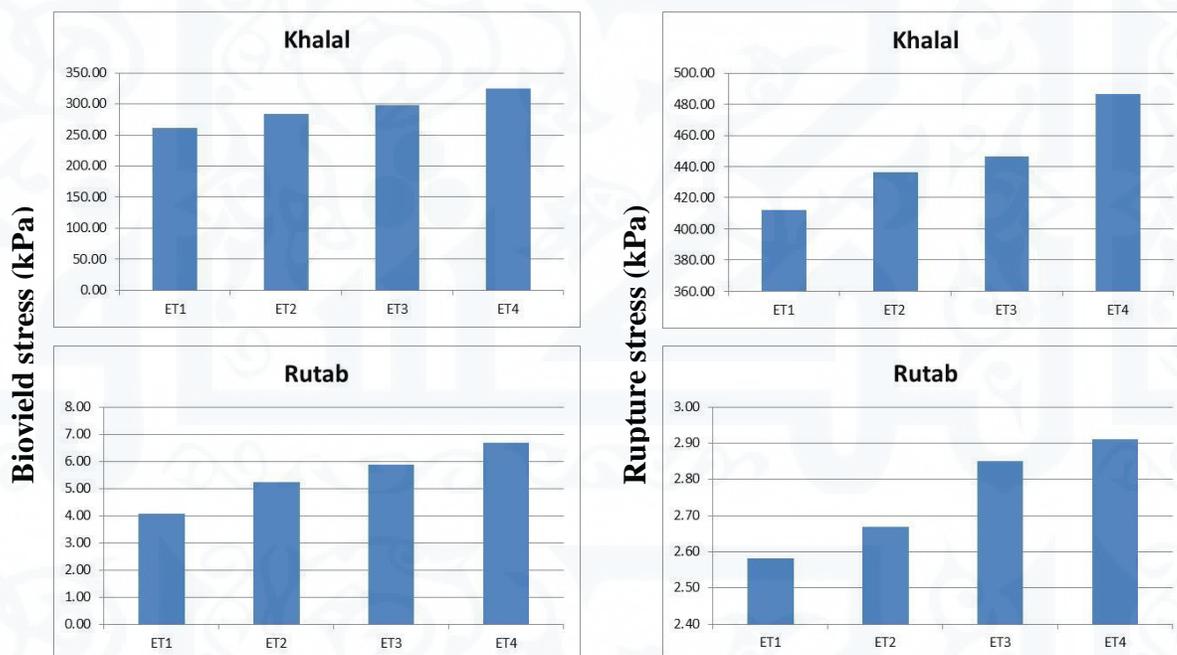
The results also showed that the values of rupture stress (σ_r) increased with decreasing water level.

For the water level treatments, the statistical analysis (at 5% level) showed significant differences for σ_r of date fruits during the three stages of ripening (Khalaal, Rutab and Tamr).

2.7. Rupture strain (ϵ_r)

From the calculated results of rupture strain for date fruits at different ripening stages with different water levels, as shown in table (3) and figure (8-a), it can be found that the rupture strain decreased from Khalaal to Tamr stages, with Talees and Taghit varieties, but in the case of Khudari variety the rupture strain increased from Khalaal to Rutab stages then decreased in Tamr stage.

In case of ET1 treatment, the values of rupture strain were 0.56, 0.40, and 0.21 mm/mm for Khalaal, Rutab and Tamr stages, respectively. In case of ET2 treatment, the values of rupture strain were 0.59, 0.39, and 0.21 mm/mm for Khalaal, Rutab and Tamr stages, respectively. In case of ET3 treatment, the values of rupture strain were 0.58, 0.41, and 0.22 mm/mm for Khalaal, Rutab and Tamr stages, respectively. In case of ET4 treatment, the values of rupture strain were 0.61, 0.43, and 0.24 mm/mm for Khalaal, Rutab and Tamr stages, respectively.



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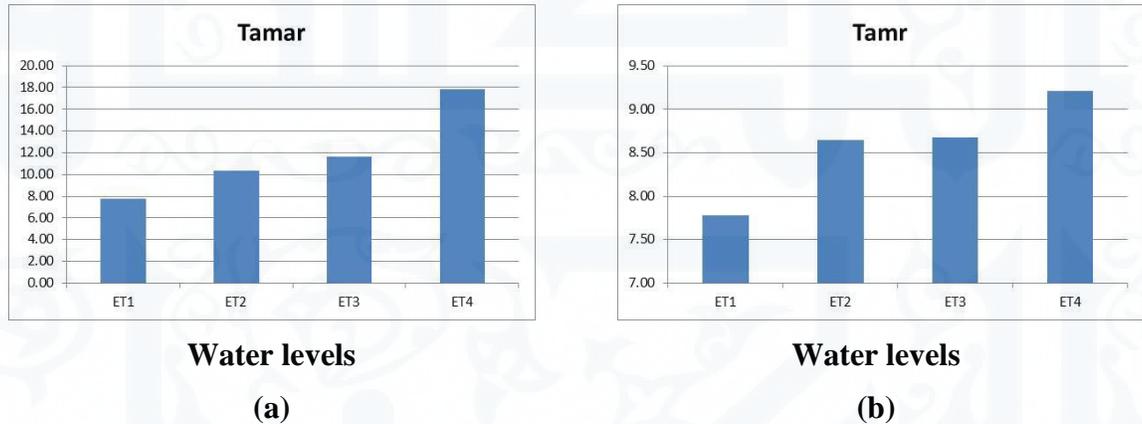


Fig. (7): Bioyield stress (σ_b) and rupture stress (σ_r) for different water levels at different ripening stages of date fruit.

The results also showed that the values of rupture strain (ϵ_r) increased with decreasing water level.

For the three varieties, the statistical analysis (at 5% level) showed significant differences for ϵ_r of date fruits during the three stages of ripening (Khalaal, Rutab and Tamr).

2.8. Rupture energy (RE)

The average values of rupture energy (RE) for date fruits at different ripening stages and water levels are shown in table (1) and figure (8-b). It is clear that, the rupture energy (RE) decreased from Khalaal to Rutab stage, while increased from Rutab to Tamr, with all different varieties.

In case of ET1 treatment, the values of RE were 0.1184, 0.00124, and 0.0213 MJ/m³ for Khalaal, Rutab and Tamr stages, respectively. In case of ET2 treatment, the values of RE were 0.1268, 0.00486, and 0.01158 MJ/m³ for Khalaal, Rutab and Tamr stages, respectively. In case of ET3 treatment, the values of RE were 0.21356, 0.00865, and 0.01195 MJ/m³ for Khalaal, Rutab and Tamr stages, respectively. In case of ET4 treatment, the values of RE were 0.26033, 0.0134, and 0.0223 MJ/m³ for Khalaal, Rutab and Tamr stages, respectively.

The results also showed that the values of RE increased with decreasing water level.

For the three varieties, the statistical analysis (at 5% level) showed significant differences for RE of date fruits during the three stages of ripening (Khalaal, Rutab and Tamr). In general, the mechanical properties of date fruit are influenced by varieties and ripening stage. As concluded from the results of the present study, each of E, FC, σ_b , σ_r and RE decreased from Khalaal to Rutab stage then increased at Tamr stage. The physical and mechanical properties of Talees date fruit under four water levels are important in designing machine used for harvesting and post harvest handling of dates during ripening stages.

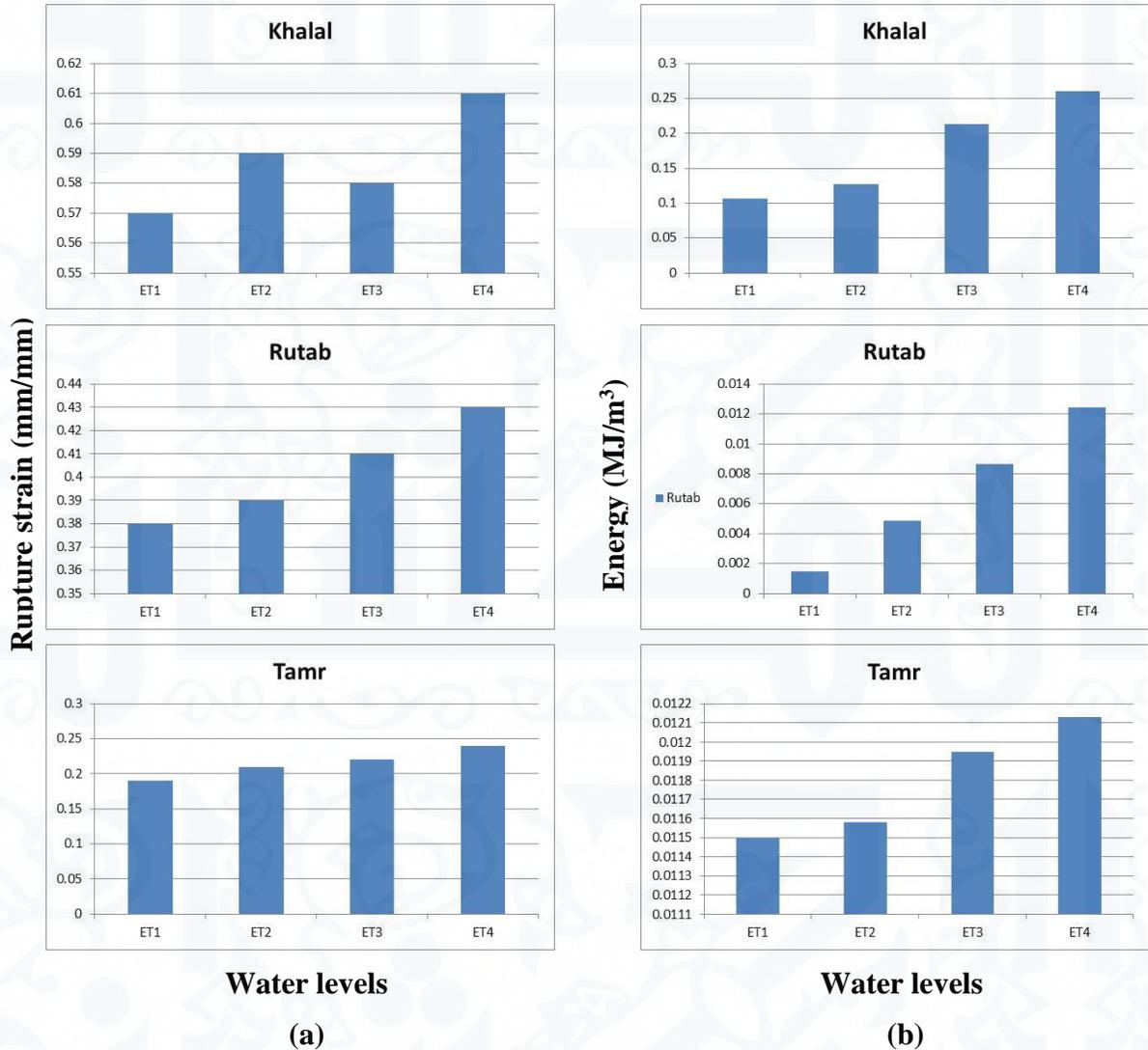


Fig. (8): Rupture strain (ϵ_r) and energy (RE) for different water levels at different ripening stages of date fruit.

3. Predicting the height of packing box

In order to get optimum (prediction) of the height of packing box the following procedure was applied.

Applying equations (10) and (11) considering the following assumption:

$d_1 = d_2 =$ fruit thickness.

$E_1 = E_2 =$ Modulus of elasticity for date fruit.

$\mu_1 = \mu_2 =$ Poisson ratio of date fruit (the absolute value of the transverse strain to the corresponding axial strain resulting from uniformly distributed axial stress below the proportional limit of the material, it was measured ≈ 0.4 .

l = Fruit length.

P_{max} = Bioyield stress of date fruit.

Substitute equation (10) in equation (11) use try and error method to calculate the maximum allowable force (F_{max}) for the three varieties in Rutab stage (the bioyield stress in Rutab stage is less than other stages), the values of n , H_{th} , and H_{act} can be calculated as shown in table (4).

Therefore, the maximum heights of packing box which does not result in mechanical damage were 267.12, 503.41, 557.64 and 716.49 mm for ET1, ET2, ET3 and ET4, respectively.

Table (4): The calculation results of F_{max} , H_{th} , and H_{act} .

	ET1	ET2	ET3	ET4
F_{max}, N	3.8	6.95	7	7.8
N	33.25	2.67	70.92	91.02
H_{th}, mm	400.68	755.12	836.45	1074
H_{act}, mm	267.12	503.41	557.64	716.49

CONCLUSION

The obtained results of physical and mechanical properties of the three date fruit varieties during three stages of ripening can be summarized as follows:

1. There were significant differences between ripening stages of date fruits for most physical properties.
2. There were significant differences between ripening stages of date fruits for mechanical properties.
3. For different water levels, the values of E, FC, σ_b , σ_r and RE decreased from Khalaal to Rutab stage then increased from Rutab to Tamr stages.
4. The different measured mechanical properties followed the same trend which reflected their state behavior at the three stages same of ripening for the three tested varieties: decreasing through Khalaal to Rutab stages then increasing through Rutab to Tamr stages.
5. The maximum heights of packing box are 267.12, 503.41, 557.64 and 716.49 mm for ET1, ET2, ET3 and ET4, respectively.



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