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Original article

The effect of drought stress and seed deterioration on cardinal temperatures of safflower (*Carthamus tinctorius* L.)

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Introduction
One of the most important stages in the life cycle is germination, which is controlled by various environmental and genetic factors. Temperature and water potential are the most important factors in germination control. Different models for quantization of germination response to temperature and osmotic potential have been used. Quantification of germination response to osmotic potential and temperature is possible using non-liner regression models. Therefore, this research was carried out to determine the cardinal temperature of germination (base temperature, optimum and maximum germination) of safflower of Sofeh cultivar under different osmotic stress (drought stress) conditions and seed deterioration.

Material and methods
In this study germination response to water potential in different temperature were studied. Treatments included osmotic levels (0, -0.4 and -0.8 MPa), temperature (5, 10, 15, 20, 30, 35 and 40 °C) and seed deterioration (0 and 5 days). Ccumulative germination response of seeds to differential water potential and temperature were quantified using three-parameter sigmoidal model. For quantifying response of germination rate to temperature for different osmotic potential were used of 3 non-linear regression models (segmented, dent-like and beta). The root mean square of errors (RMSE), coefficient of determination (R^2), CV and SE for relationship between the observed and the predicted germination percentage were used to select the superior model from among the employed methods. Germination percentage and time to 50% maximum seed germination of safflower were calculated for the different temperatures and osmotic potential by fitting 3-parameter sigmoidal functions to cumulative germination data.

Results
Results indicated that temperature in addition to germination percentage also on germination rate was effective. Also results showed that germination percentage and germination rate increased with increasing temperature, while germination percentage and germination rate reduced as a result of water potential increment. Results indicated that under different osmotic potential as 0, -0.4 and -0.8 MPa, the segmented model estimated base temperature as 2.23, 3.67 and 4.33 °C, the dent model estimated base temperature as 3, 3.96 and 4.33 °C, the beta model estimated base temperature as -1.22, -1.28 and -2.28 °C, the segmented model estimated

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optimum temperature as 23.05, 25.44 and 24.19 °C, the optimum temperature using beta model as 28.89, 28.99 and 26.46 °C, the dent-like model estimated lower limit of optimum temperature and upper limit of optimum temperature as 21.12, 21.92 and 20.16 and 30.07, 25 and 23.27 °C, ceiling temperature using segmented model were 40, 40 and 35 °C, using dent-like model were 40, 39.83 and 35 °C, using beta model were 40, 35 and 34.82 °C, the segmented model estimated fo as 23.02, 69.51 and 84.17 h, the dent-like model estimated as 27, 75.99 and 83.87 h and using beta model were 26.09, 75.09 and 103.41 h, respectively. In compared 3 models according to the root mean square of errors (RMSE) of germination time, the coefficient of determination (R2), CV and SE the best model for determination of cardinal temperatures of seed control of safflower for 0 MPa was dent-like model and for -0.4 and -0.8 MPa was segmented model and for seed deterioration of safflower in all osmotic potential was segmented model. In general, results indicated that lower limit of optimum temperature and upper limit of optimum temperature and ceiling temperature reduced but fo increased as a result of water potential increment.

Conclusion

Germination of safflower response to different temperatures and osmotic potentials, led to acceptable results. Utilizing the output of non-liner models at different temperatures can be useful in prediction of germination rate in different water potential.

Keywords: Accelerating aging, Cardinal temperatures, Germination percentage, Non-liner regression models, Osmotic potential

Table 1. Segmented, dent-like and beta models that were fitted to germination rate data for determining cardinal temperatures for *Carthamus tinctorius* L. seeds.

Function	Formula
Dent-like (2) (Piper, 1996)	$f(T)= (T-T_b)/(T_{o1}-T_b)$ if $Tb< T\leq T_{o1}$ $f(T)= (Tc-T)/(Tc-T_{o2})$ if $T_{o2}< T\leq T_c$ $f(T)= 1$ if $T_{o1}< T\leq T_{o2}$ $f(T)= 0$ if $T\leq T_b$ or $T\geq T_c$
Segmented (3) (Soltani et al., 2006)	$f(T)= (T-T_b)/(T_o-T_b)$ if $T_b< T\leq T_o$ $f(T)= [1-(T-T_o)/(Tc-T_o)]$ if $T_o< T\leq T_c$ $f(T)= 0$ if $T\leq T_b$ or $T\geq T_c$
Beta (4) (Soltani et al., 2006)	$f(T)= ((T_c-T)/(T_c-T_o))*((T-T_b)/(T_o-T_b))^{(To-Tb)/(Tc-To)}$

T_b, T_o, T_m, T_{o1}, T_{o2}, and fo are base temperature, optimum temperature, ceiling temperature, lower limit of optimum temperature, upper limit of optimum temperature, minimum time to reach a given percentile.

Table 2. Estimated parameters for the non-liner regression models for non-deterioration seeds of *Carthamus tinctorius* L. Tb, To, Tm, To1, To2, fo, a and b are base temperature, optimum temperature, ceiling temperature, lower limit of optimum temperature, upper limit of optimum temperature, minimum time to reach a given percentile, coefficient of regression, intercept and slope of linear regression between predicted against observed germination rate, respectively. Numbers in parentheses represent standard error of the mean.

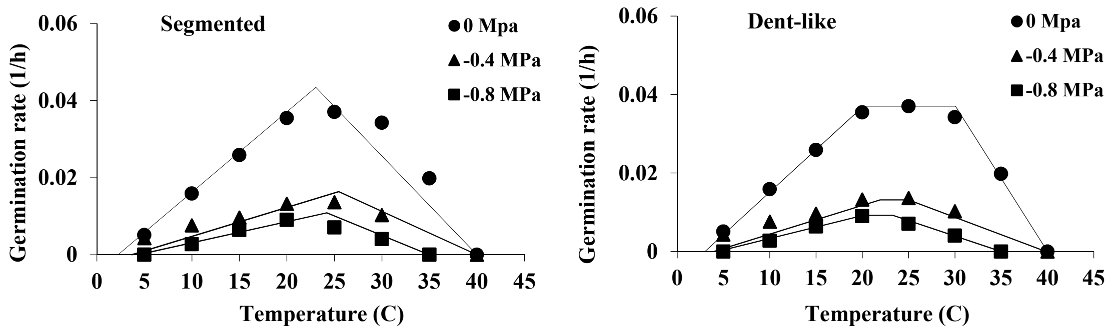
Model	Segmented			Dent- like			Beta		
Parameter	0	-0.4	-0.8	0	-0.4	-0.8	0	-0.4	-0.8
t_b	2.23(0.4)	3.67(0.1)	4.33(0.8)	3(0.26)	3.9(1.09)	4.3(0.8)	-2.3(1.3)	-1.3(1.3)	-1.22(1.4)
t_o	23.05(0.53)	25.44(0.59)	24.19(0.65)	-	-	-	28.9(0.3)	29.0(5.3)	26.46(0.7)
t_{o1}	-	-	-	20.1(1.9)	21.9(4.4)	20.2(7.3)	-	-	-
t_{o2}	-	-	-	30.1(0.5)	25(5.32)	23.3(3.5)	-	-	-
tm	40(0.3)	40(0.53)	35(0.41)	40(0.3)	39.8(5.4)	35(0.51)	37.6(0.1)	35.0(3.1)	34.8(0.7)
f_o	23.0(0.9)	69.5(2.8)	84.2(3.1)	27(1.6)	76.0(10.4)	83.9(9.4)	26.1(0.4)	75.1(4.2)	103(25.)
a	0.98	0.98	1.25	0.99	0.98	0.98	1.001	0.99	1.01
b	0.0004	0.0001	0.00009	0.0002	0.0002	0.0004	0.00003	0.0001	0.001
R^2	0.98	0.98	0.96	0.99	0.98	0.99	0.99	0.96	0.82
RMSE	0.002	0.0006	0.0007	0.0007	0.002	0.01	0.001	0.002	0.001
CV%	*10.13*	*7.52*	*16.76*	*3.96*	*23.91*	*29.65*	*7.33*	*23.91*	*28.09*

Table 3. Estimated parameters for the non-liner regression models for deterioration seeds of *Carthamus tinctorius* L. T_b, T_o, T_m, T_{o1}, T_{o2}, f_o, a and b are base temperature, optimum temperature, ceiling temperature, lower limit of optimum temperature, upper limit of optimum temperature, minimum time to reach a given percentile, coefficient of regression, intercept and slope of linear regression between predicted against observed germination rate, respectively. Numbers in parentheses represent standard error of the mean.

Model	Segmented			Dent- like			Beta		
Parameter	0	-0.4	-0.8	0	-0.4	-0.8	0	-0.4	-0.8
t_b	4.88(0.11)	6.61(0.21)	11.24(0.20)	5.1(0.85)	5.88(0.15)	11.33(0.65)	-	-	-
t_o	25.17(1.24)	20.78(1.7)	20.2(0.32)	-	-	-	-	-	-
t_{o1}	-	-	-	24.17(2.52)	19.92(3.54)	21.2(1.23)	-	-	-
t_{o2}	-	-	-	26.11(2.54)	22.14(2.54)	21.21(2.85)	-	-	-
tm	40.0(0.3)	35.0(0.53)	35(0.41)	40.0(0.35)	35.0(5.43)	35(0.51)	-	-	-
f_o	41.01(0.87)	115.69(3.94)	243.38(5.75)	41.98(1.59)	118.48(9.14)	227.89(7.65)	-	-	-
a	0.98	0.98	0.98	0.99	0.99	0.98	-	-	-
b	0.0002	0.0001	0.0002	0.0002	0.0004	0.0003	-	-	-
R^2	0.97	0.98	0.98	0.95	0.92	0.90	-	-	-
RMSE	0.001	0.0003	0.0005	0.0009	0.0007	0.006	-	-	-
CV%	*7.43*	*9.07*	*8.46*	*12.98*	*16.47*	*21.55*	-	-	-

Table 4. Effect of different osmotic potentials on base temperatures of *Carthamus tinctorius* L. Numbers in parentheses represent standard error of the mean.

Osmotic potential (MPa)	Aged seed (Day)	Model		
		Segmented	Dent-like	Beta
0	0	2.23(0.44)	3.0(0.26)	-2.28(1.34)
	5	4.88(0.11)	5.1(0.85)	-
-0.4	0	3.67(0.11)	3.96(1.09)	-1.28(1.32)
	5	6.61(0.21)	5.88(0.15)	-
-0.8	0	4.33(0.81)	4.33(0.87)	-1.22(1.44)
	5	11.24(0.20)	11.33(0.65)	-



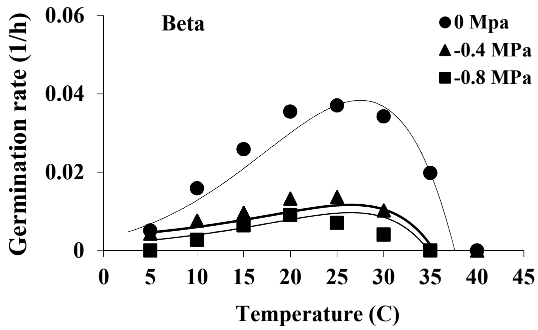


Fig. 1. Predicted (lines) and observed (symbols) germination rate non-deterioration seeds of *Carthamus tinctorius* L. at different temperatures for different germination percentiles (t_{10}, t_{30} and t_{50}) using segmented, dent-like and beta models

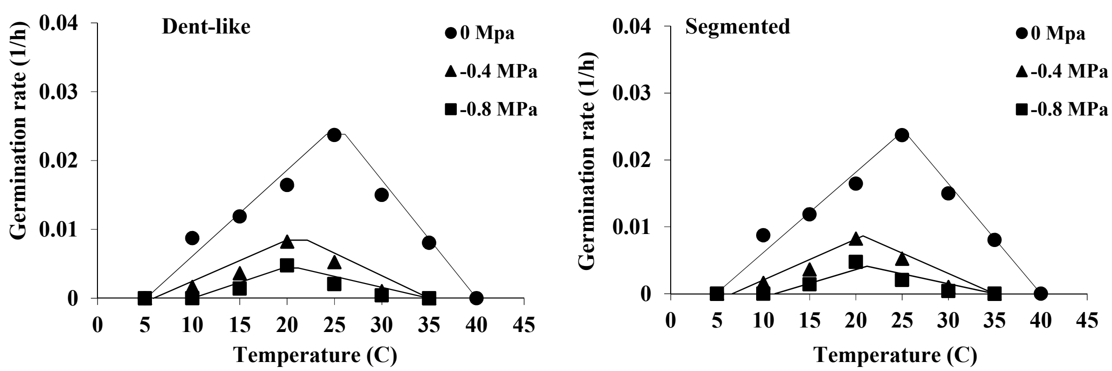


Fig. 2. Predicted (lines) and observed (symbols) germination rate deterioration seeds of *Carthamus tinctorius* L. at different temperatures for different germination percentiles (t_{10}, t_{30} and t_{50}) using segmented and dent-like models

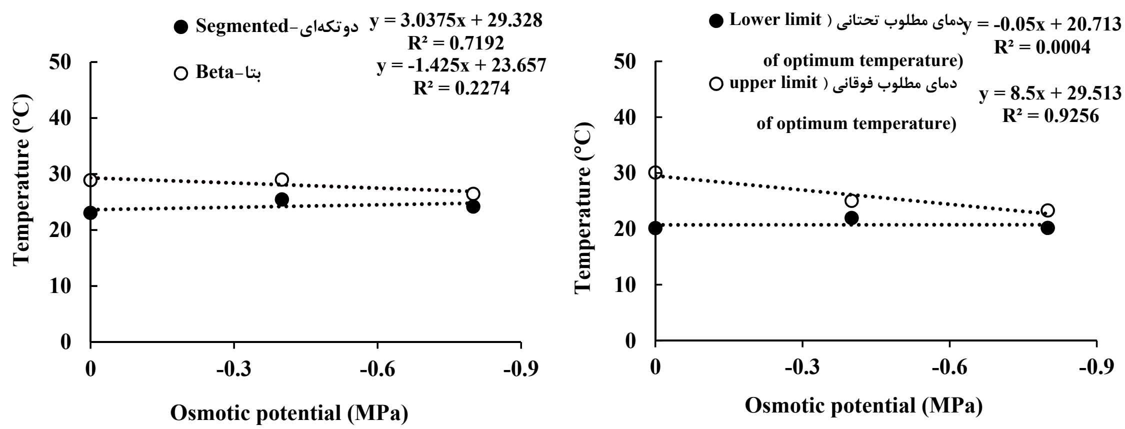


Fig. 3. Effect of osmotic potential on optimum temperature, lower limit of optimum temperature and upper limit of optimum temperature achieved by segmented, dent-like and beta models for non-deterioration seeds of *Carthamus tinctorius* L

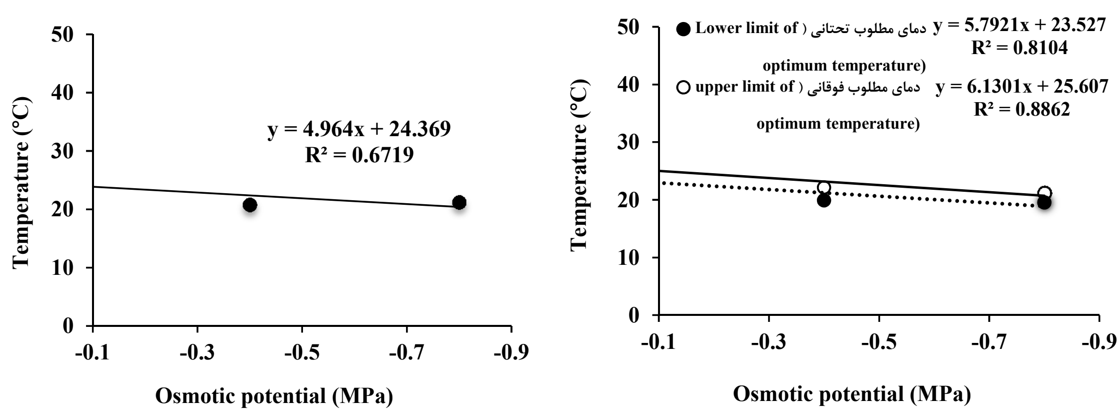


Fig. 4. Effect of osmotic potential on optimum temperature, lower limit of optimum temperature and upper limit of optimum temperature achieved by segmented, dent-like and beta models for deterioration seeds of *Carthamus tinctorius* L.

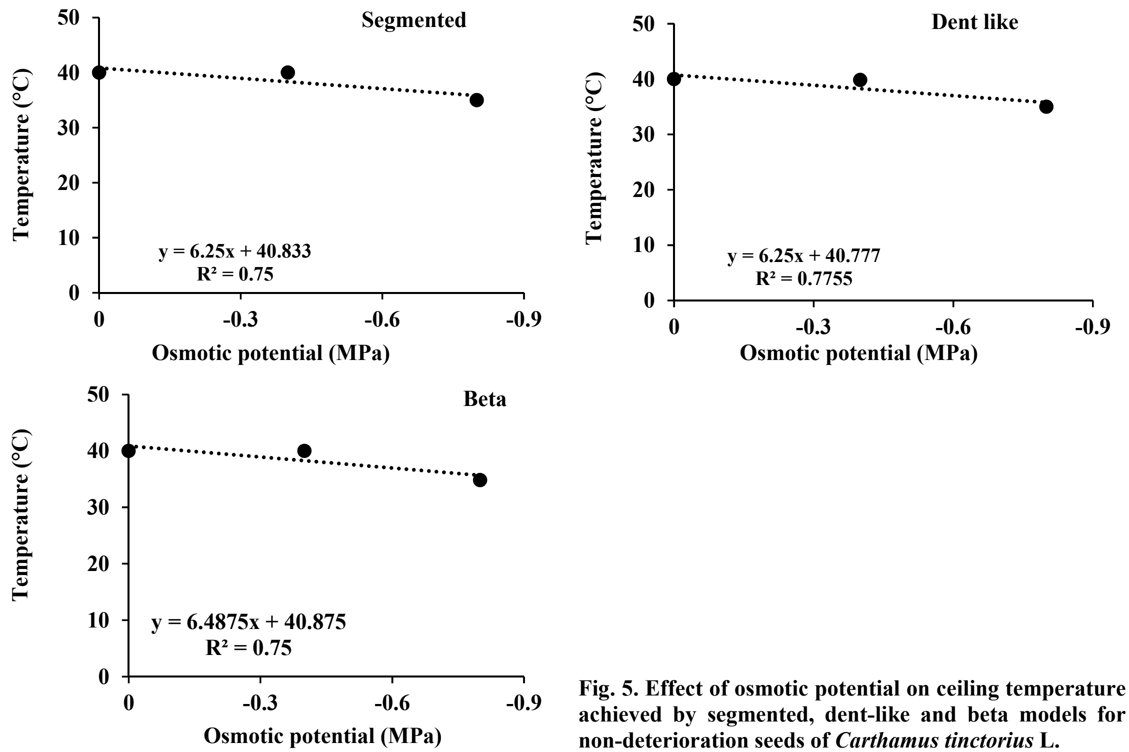


Fig. 5. Effect of osmotic potential on ceiling temperature achieved by segmented, dent-like and beta models for non-deterioration seeds of *Carthamus tinctorius* L.

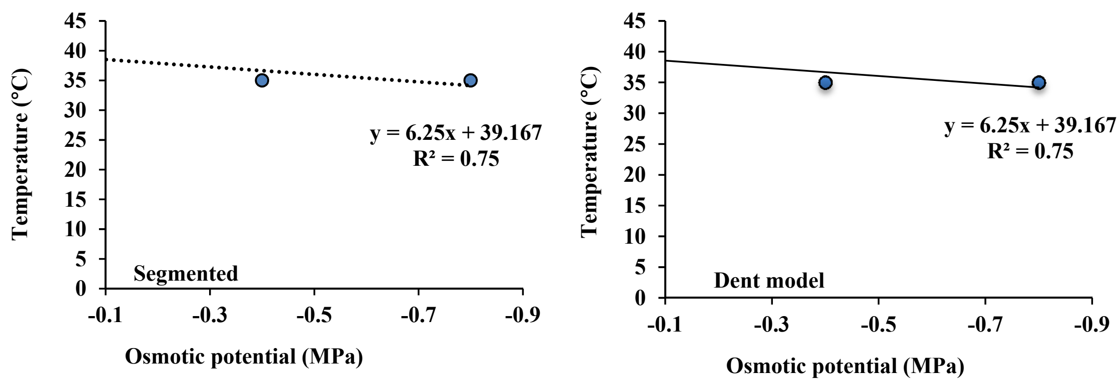
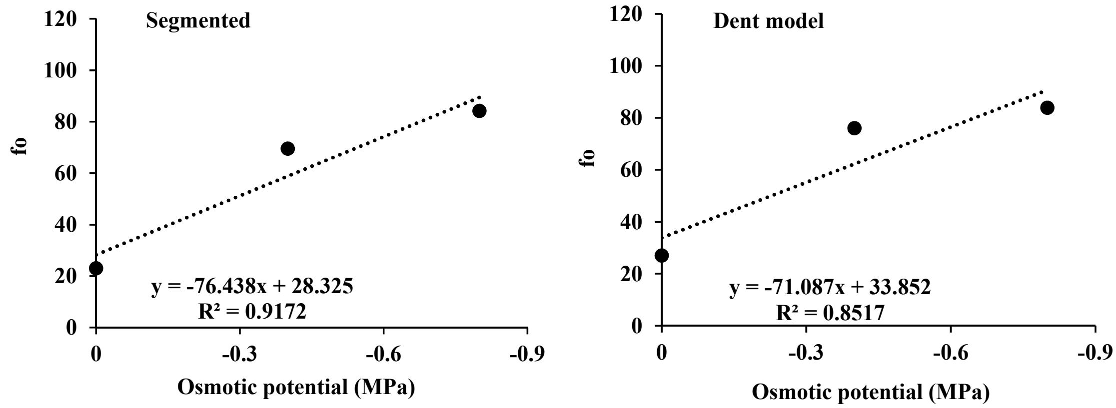


Fig. 6. Effect of osmotic potential on ceiling temperature achieved by segmented, dent-like and beta models for deterioration seeds of *Carthamus tinctorius* L.



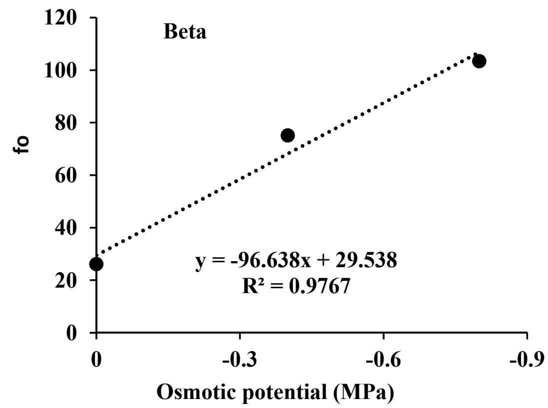


Fig. 7. Effect of osmotic potential on f_o achieved by segmented, dent-like and beta models for non-deterioration seeds of *Carthamus tinctorius* L.seed

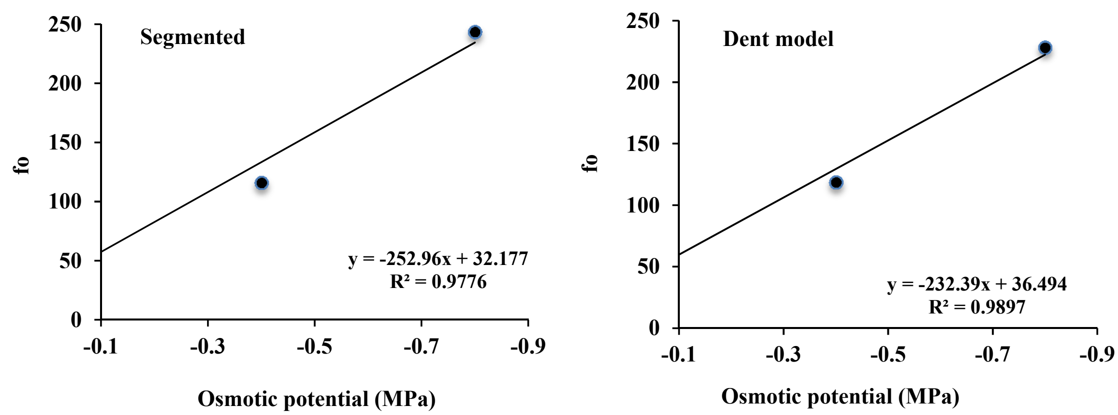


Fig. 8. Effect of osmotic potential on f_o achieved by segmented, dent-like and beta models for deterioration seeds of *Carthamus tinctorius* L.