Introduction

Engineering properties of agricultural materials are important information required to design handling, cleaning, conveying, grading, packaging, and storage systems (Tabatabaeefar 2003). Settling depth of fruits and vegetables in water is of the hydrodynamic properties defined for targets with density lower than the density of water. It is a depth that a target dropped from a height will reach to that and returns to the water surface. Settling depth of fruits and vegetables is necessary for determining the depth of water in channel to avoid the fruit contact with channel bottom (Mohsenin 1986).

Kheiralipour (2014) theoretically modeled the settling depth of fruits and vegetables with the density lower than the density of water, \( \rho_f < \rho_w \), as following formula:

\[
    d = \frac{2d_0 \left( \rho_f - \rho_a \right) V^{-2/n}}{\left( \rho_a - \rho_w \right) V^{-2/n} + k \mu_w \rho_w S_h \left( 2gd_0 \left( 1 - \frac{\rho}{\rho_f} \right) \right)^{-2/n}}
\]

where \( d \) is settling depth of fruit, \( d_0 \) is dropping height, \( \rho_f \) is target density, \( \rho_a \) is air density, \( V \) is target volume, \( \rho_w \) is water density, \( \mu_w \) is the static viscosity of water, \( S_h \) is shape factor, \( g \) is acceleration of gravity, and \( k \) and \( n \) are constant factors. The more important effective parameters on settling depth are dropping height, density, mass, and volume of target (Kheiralipour 2014).

In the world, the total production of apple fruit (Malus domestica Borkh L.) is around 76.38 million tons. China is the first apple producer in the world with 37 million tons annual production. After United States, Turkey, Poland, India, and Italy, Islamic Republic of Iran with production of 17.00 million tons is ranked as the seventh producer country (FAOSTAT, 2012). In the literature, physical characteristics of apple fruit were investigated and reported (Tabatabaeefar and Rajabipour 2005; Kheiralipour et al. 2008; Jalali et al. 2013) but there is no information about settling depth of apple fruit. So, the decision in this research was to develop experimental model of apple settling depth based on its physical properties. The settling depth of apple, Red Delicious variety, was determined and modeled considering theoretical model developed by Kheiralipour (2014) and multivariate regression procedure.

Abstract

Settling depth of targets, with a density lower than the density of water, is a distance between water surface and a depth that the target reaches after dropping from a height. In this research, settling depth of apple was determined by a water column and a digital camera and then was experimentally modeled using multivariate regression program coded in MATLAB software. The considered parameters in multivariate modeling were physical characteristics (density, mass, and volume) and dropping height of the target. The characteristics were determined by standard methods. The best models were based on the density, dropping height and volume/mass with coefficient of determination (R²), and mean square error (MSE) of 0.90 and 4.08, respectively.
Materials and Methods

Theory

In this research, equation (1) was considered for experimental modeling of settling of targets in water. By reversing $d$, equation (1) is changes to:

$$\frac{1}{d} = \left( \rho_w - \rho_f \right) V^{\frac{1}{2}} + K \mu_0 \rho_w^{-1-n} S_k \left( 2g \rho_w \left( 1 - \frac{\rho_f}{\rho_w} \right) \right)^{-\frac{n}{2}}$$  \hspace{1cm} (2)

Equation (2) can be broken as following:

$$\frac{1}{d} = \frac{\left( \rho_w - \rho_f \right)}{2d_k \left( \rho_f - \rho_w \right)} V^{\frac{1}{2}} + \frac{K \mu_0 \rho_w^{-1-n} S_k \left( 2g \rho_w \left( 1 - \frac{\rho_f}{\rho_w} \right) \right)^{-\frac{n}{2}}}{2d_k \left( \rho_f - \rho_w \right)} V^{\frac{1}{2}}$$  \hspace{1cm} (3)

After simplification, equation (3) would be changed as following:

$$\frac{1}{d} = \frac{1}{2d_k \left( \rho_f - \rho_w \right)} \left( \rho_w - \rho_f \right) + \frac{K \mu_0 \rho_w^{-1-n} S_k \left( 2g \rho_w \left( 1 - \frac{\rho_f}{\rho_w} \right) \right)^{-\frac{n}{2}} \rho_f}{2d_k \left( \rho_f - \rho_w \right)}$$  \hspace{1cm} (4)

The parameters $\frac{1}{2d_k}$ and $\frac{K \mu_0 \rho_w^{-1-n} S_k \left( 2g \rho_w \left( 1 - \frac{\rho_f}{\rho_w} \right) \right)^{-\frac{n}{2}} \rho_f}{2d_k}$ in equation (4) are replaced by $K_2$ and $K_3$. So equation (5) can be:

$$\frac{1}{d} = K_2 d_0^{-1} \left( \rho_w - \rho_f \right) \rho_f^{-\frac{n}{2}} + K_3 S_k d_0^{-n} \rho_f^{-1-n} V^{\frac{1}{2}}$$  \hspace{1cm} (5)

The air density ($\rho_a$) can be neglected in previous equation and $K_2 \rho_w = K_1$, so:

$$\frac{1}{d} = K_1 d_0^{-1} \rho_f^{-1-n} - K_2 d_0^{-n} + K_3 S_k d_0^{-n} \rho_f^{-1-n} V^{\frac{1}{2}}$$  \hspace{1cm} (6)

The volume in the equation 6 can be replaced by target mass, $m$, as following:

$$\frac{1}{d} = K_1 d_0^{-1} \rho_f^{-1-n} - K_2 d_0^{-n} + K_3 S_k d_0^{-n} \rho_f^{-1-n} m^{\frac{1}{2}}$$  \hspace{1cm} (7)

So, descent depth of target can be modeled using equations (8) or (9):

$$\frac{1}{d} = A d_0^{-1} \rho_f^{-1-n} + B S_k d_0^{-n} \rho_f^{-1-n} V^{\frac{1}{2}} + F d_0^{-1} + G$$  \hspace{1cm} (8)

$$\frac{1}{d} = A d_0^{-1} \rho_f^{-1-n} + B S_k d_0^{-n} \rho_f^{-1-n} m^{\frac{1}{2}} + F d_0^{-1} + G$$  \hspace{1cm} (9)

where $A$, $B$, $C$, $D$, $E$, $F$, and $G$ are constant factors. The constant coefficient $G$ was added to the end of the equations (8) and (9) as an error in experimental modeling. The difference between equations (8) and (9) is volume and mass, only.

Experiments

The targets in this research were apple fruit from Red Delicious variety. Target mass was determined by Precisa electronic balance (Model: 3100c) with accuracy of 0.1 g. Volume and density of the targets were determined by the water displacement method (Mohsenin 1986).

A water column ($35 \times 35 \times 90$ cm$^3$) was constructed by glass with thickness of 8 mm. It was filled by water to a height of 80 cm. Each target was placed on a specific height (dropping height = 10, 25, and 50 cm) on top of the water surface, so that the largest areas of them were parallel to the surface of the water column. In order to determine settling depth of the targets a digital camera (Sony, Model) with 25 frames per second recorded the moving of them from the dropping height point to the end of the target’s settling depth in water column. Each fruit was tested three times in each dropping height. In order to correctly determine the settling depth of the fruits, Video to Frame Software was used to change each video film to corresponding images (Fig. 1).

Multivariate modeling

The obtained data were considered for modeling of settling depth of apples using equation (8) and (9). In the present research, the projected area of the targets was not determined due to low effect on the terminal velocity (Jordan and Clark 2004; Kheiralipour et al. 2010). So, the equations (8) and (9) can be changed to:
where, \( H \) is a new constant factor instead of \( B_S \).

The multivariate regression method was used for modeling settling depth of the targets. For this, a program was coded in MATLAB Software. The program was applied “nlinfit” command in the software. The program was able to calculate determination coefficient (\( R^2 \)) and mean square error (MSE) of each model.

**Results and Discussions**

Some physical properties of the targets were presented in Table 1. In this table, besides density, volume and mass, settling depth of the targets when dropping from the different heights of 10 cm (\( d_{10} \)), 25 cm (\( d_{25} \)), and 50 cm (\( d_{50} \)) were listed.

Settling depth of all experimented targets was plotted in Figure 2. As shown in this figure, by increasing the dropping height from 10–50 cm, the settling depth was increased. As can be seen in this figure, the settling depth of all targets was not uniformly increased. This is due to effect of other parameters of target on the settling depth.

As can be seen in this figure, most of the lines to show the relations between settling depth and physical attributes of the fruit have increasing trend by the increase in target mass, volume, and density. This trend is more detectable for Figure 2A. Also by comparing all parts of Figure 2, it is observed that the effect of dropping height is higher than that of mass, volume, and density of the target.

Multivariate models of settling depth of the targets were done based on equations (10) and (11) for each dropping height individually. The models were shown in Tables 2–4 for dropping height of 10, 25, and 50 cm, respectively.

\[
\frac{1}{d} = Ad_0^{-1}\rho_f^{-1} + Hd_0\rho_f^{-1}\sqrt{\rho_f} + Fd_0^{-1} + G \quad (10)
\]

\[
\frac{1}{d} = Ad_0^{-1}\rho_f^{-1} + Hd_0\rho_f^{-1}\sqrt{\rho_f} + Fd_0^{-1} + G \quad (11)
\]

In Table 2, model No. 1, 2, and 3 (single-variate) with \( R^2 = 0.1021, 0.0199, \) and 0.0090, respectively, show that density, volume, and mass of the targets cannot individually model the settling depth from 10 cm dropping height. Also other models which are multivariate, with a coefficient determination of 0.3358–0.3994 cannot strongly predict the settling depth with 10 cm dropping height.

Models No. 1, 2, and 3 in Table 3, are same as those in Table 2. The other models in Table 3 have the determination coefficients higher than the corresponding values of Table 2.

Also, Models No. 1, 2, and 3 in Table 4 have low determination coefficient same as corresponding values in Tables 2 and 3. The other models show that settling depth of apple dropped from height of 25 cm can be better modeled than the settling depth of targets dropped from the height of 10 cm (Table 2).

Table 1. Some physical properties of the targets.

|                  | Minimum | Mean | Maximum | Standard deviation |
|------------------|---------|------|---------|-------------------|
| Density (g/cm³)  | 0.82    | 0.86 | 0.88    | 0.02              |
| Volume (cm³)     | 123.78  | 162.64 | 211.00 | 25.84            |
| Mass (g)         | 104.44  | 139.40 | 171.94 | 20.32            |
| \( d_{10} \) (cm) | 25.7    | 30.3  | 34.0    | 2.2               |
| \( d_{25} \) (cm) | 33.9    | 38.0  | 42.0    | 2.0               |
| \( d_{50} \) (cm) | 39.0    | 44.6  | 51.0    | 3.4               |

\( d_{10}, d_{25} \) and \( d_{50} \) are settling depth of the targets when dropping from a height of \( d_0 = 10, 25 \) and 50 cm, respectively.
Table 2. Multivariate models of the settling depth of the targets with dropping height of 10 cm.

| Model No | Model | MSE     | R²    |
|----------|-------|---------|-------|
| 1        | $d = 0.0362 p_1^{-1} - 0.0090$ | $5.2246 \times 10^{-6}$ | 0.1021 |
| 2        | $d = 6.9800 \times 10^{-15} V^{4.87} + 0.033$ | $5.7015 \times 10^{-6}$ | 0.0199 |
| 3        | $d = 8.2200 \times 10^{-7} m^{-4.43} + 0.033$ | $5.7650 \times 10^{-6}$ | 0.0090 |
| 4        | $d = 341.2355 p_1^{-0.6352} V^{-0.3110} + 0.0323$ | $3.8646 \times 10^{-6}$ | 0.3358 |
| 5        | $d = 344.6594 p_1^{-0.1555} m^{-0.3143} V^{-0.6352} + 0.0328$ | $3.8645 \times 10^{-6}$ | 0.3358 |
| 6        | $d = -0.2955 p_1^{-1} + 0.0067 p_1^{-1} V^{-0.6352} m^{-0.3110} + 0.03502$ | $3.5561 \times 10^{-6}$ | 0.3994 |
| 7        | $d = -0.2955 p_1^{-1} + 0.0067 p_1^{-1} V^{-0.6352} m^{-0.3110} + 0.3502$ | $3.5561 \times 10^{-6}$ | 0.3994 |

Table 3. Multivariate models of the settling depth of apple with dropping height of 25 cm.

| Model No | Model | MSE     | R²    |
|----------|-------|---------|-------|
| 1        | $d = 0.0205 p_1^{-1} + 0.0025$ | $1.6152 \times 10^{-6}$ | 0.1057 |
| 2        | $d = 2.9694 \times 10^{-9} V^{2.243} + 0.0257$ | $1.2514 \times 10^{-6}$ | 0.3068 |
| 3        | $d = 1.7067 \times 10^{-9} m^{-0.6352} + 0.0256$ | $1.1576 \times 10^{-6}$ | 0.3588 |
| 4        | $d = 0.2515 p_1^{-0.01744} V^{-0.4973} - 0.1920$ | $6.7594 \times 10^{-6}$ | 0.6256 |
| 5        | $d = 0.2020 p_1^{-0.1024} m^{-0.4844} - 0.1419$ | $6.8423 \times 10^{-6}$ | 0.6256 |
| 6        | $d = 0.0631 p_1^{-1} + 2.2925 \times 10^4 p_1^{-1} V^{-0.3110} - 0.0498$ | $5.5090 \times 10^{-6}$ | 0.6948 |
| 7        | $d = 0.1172 p_1^{-1} + 0.7941 p_1^{-1} m^{-0.6352} - 0.1228$ | $5.9653 \times 10^{-6}$ | 0.6699 |

Table 4. Multivariate models of the settling depth of the targets with dropping height of 50 cm.

| Model No | Model | MSE     | R²    |
|----------|-------|---------|-------|
| 1        | $d = 0.0159 p_1^{-1} + 0.0040$ | $2.7568 \times 10^{-6}$ | 0.0398 |
| 2        | $d = 1.0505 \times 10^{-9} V^{0.0124} + 0.0218$ | $2.2829 \times 10^{-6}$ | 0.2048 |
| 3        | $d = 1.3282 \times 10^{-9} m^{-0.2792} + 0.0217$ | $2.2035 \times 10^{-6}$ | 0.2324 |
| 4        | $d = 1.0841 p_1^{-0.0087} V^{-0.0087} - 1.0299$ | $1.7423 \times 10^{-6}$ | 0.3942 |
| 5        | $d = 1.7559 p_1^{-0.5000} m^{-0.0049} - 1.6999$ | $1.7409 \times 10^{-6}$ | 0.3942 |
| 6        | $d = 0.0977 p_1^{-1} + 1.4534 p_1^{-1} V^{-0.4973} m^{-0.6352} - 0.1015$ | $1.6627 \times 10^{-6}$ | 0.4211 |
| 7        | $d = 0.0977 p_1^{-1} + 1.4534 p_1^{-1} V^{-0.4973} m^{-0.6352} - 0.1015$ | $1.6625 \times 10^{-6}$ | 0.4211 |

Table 5. Final multivariate models of settling depth of apple.

| Model No | Model | MSE     | R²    |
|----------|-------|---------|-------|
| 1        | $d = -234.4133 d_1^{-1} p_1^{-1} + 0.0019 d_4^{-3.7568} p_1^{1.9487} m^{-1.8470} - 209.6996 d_1^{-1} + 32.7118$ | $4.0752$ | 0.9004 |
| 2        | $d = -234.4135 d_1^{-1} p_1^{-1} + 0.0019 d_4^{-3.7568} p_1^{1.9487} m^{-1.8470} - 209.6996 d_1^{-1} + 32.7118$ | $4.0752$ | 0.9004 |

Settling depth of the targets was modeled based on equations (10) and (11) but with considering all dropping heights (Table 5).

As can be seen in Table 5, the coefficient of determination and mean square error of the two models is same and equal to 0.9004 and 4.0752, respectively. By this result it can be told that both parameter groups ([1] dropping height, density and volume and [2] dropping height density and mass) can model the settling depth with same ability. Also, these models have higher coefficient of determination compare with the models in Tables 2–4.

The models in Table 5 can be used to predict the settling depth of apple, Red Delicious variety. For hydraulic handling and transporting of apple when dropped from a specific height, the settling depth can be predicted to avoid the fruit impact, for example, with channel bottom.

Conclusions

Some physical characteristics, density, volume, and mass of apple variety were determined. The settling depth of
the dropped target from different heights of 10, 25, and 50 cm was determined using a water column and a digital camera. The settling depth was experimentally modeled based on the determined parameters. Based on the best model, $R^2 = 0.9004$ and MSE = 4.0752.

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**Conflict of Interest**

None declared.

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