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*Full Length Research Paper*

# Modelling the effect of temperature on seed germination in some cucurbits

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**The prediction of germination percentage (GP) and germination speed (GS) of the seeds for some cucurbits (watermelon, melon, cucumber, summer squash, pumpkin and winter squash) was investigated by mathematical model based on temperature. The model, D = [*a - (b x T) + (c x $T^2$)*] of Uzun et al. (2001), was adapted to predict both the GP and GS in relation to 12 different temperatures, namely 12, 15, 18, 21, 24, 27, 30, 33, 36, 39, 42 and 45°C. In addition, optimum temperature (*$T_o$ = - b / 2 x c*) for GP and GS were calculated by using the coefficients obtained from the regression models developed. Observed and predicted optimum temperature ($T_o$) for GP and GS varied among species and cultivars and strong correlations were established between observed and predicted GP and GS based on temperature. The predicted $T_o$ ranged from 21.6°C (summer squash, pop. Urfa) to 27.8°C (watermelon, cv. Amazon $F_1$) for GP and from 25.5°C (winter squash) to 30.4°C (melon, cv. Hasanbey-1) for GS. These results indicated that predictions based on this mathematical model were highly reliable and that it could be confidently used to predict GP and GS for the evaluated cucurbits.**

**Key words:** Germination, modelling, temperature, cucurbit crops.

## INTRODUCTION

Appropriate temperature is probably the most important factor in regulating germination (Nerson, 2007). Temperature affects the germination capacity, the germination rate and the germination frequency alongside the incubation time (Kocabas et al., 1999). Germination speed usually increases until the temperature reaches 30 - 35°C (Roberts and Ellis, 1989). Temperature has significant effects on the onset, potential and rate of germination (Flores and Briones, 2001).

The thermal limits for germination are defined by the minimum ($T_m$), optimum ($T_o$) and maximum ($T_M$) temperatures which can determine some of the ecological limitations for the geographic distribution of the species. Optimum temperature is the temperature value which results in the highest germination speed (Hakansson et al., 2002). Optimum temperatures produce both the most rapid seed germination and plant growth. Therefore, it is useful to know the minimum, optimum and maximum temperatures for plant growth and development.

The ability to predict the germination time plays a critical role in understanding seedling establishment in both natural ecosystems and cropping systems (Wang et al., 2004). Thermal and hydrothermal time models have considerable potential to characterize and quantify the effects of seedbed environments on seed germination and seedling emergence (Forcella et al., 2000; Bradford, 2002). These models have been successfully used to predict the timing of seedling emergence in crops (Finch-Savage and Phelps, 1993) and in forage crops (Hardegree and Van Vactor, 1999) and thus influenced the yield and monetary value of crops.

Thermal time (degree-day or hour), the heat unit for plant development, is a firmly established developmental principle for plants (Fry, 1983). A thermal time model utilizes temperature for predicting seed germination and the model can be applied to a wide range of conditions. Because soil temperature is normally inadequate and greatly variable in the surface layer of soils where germination usually occurs, thermal stress often limits germination and affects the time of seedling emergence in the field (Benech-Arnold and Sanchez, 1995). The effects of temperature on seed germination and emergence for somespecies have been examined through modelling, as well as under field or laboratory conditions. Kevseroglu et al. (2000) carried out studies using some industrial plants, Dürr et al. (2001) in sugar beet, Uzun et al. (2001)

in some vegetable crops, Malcolm et al. (2003) in peach, Balkaya (2004) and Kurtar et al. (2004) in *Legume* crops, Jame and Cutforth (2004) in wheat*,* Wang et al. (2004) in winterfat, Cırak et al. (2007) in tobacco, Odabas and Mut (2007) in grain legumes and cereals, Balkaya et al. (2008) in some *Brassica* species, Knappenberger and Koller (2008) in corn. Models have been used by many researchers to determine plant growth potential, development and yield (Prusinkiewicz, 2004; Yang et al., 2004), as well as seed germination, seedling emergence times, and seedling growth potential, in recent years (Finch-Savage and Phelps, 1993; Hardegree et al., 2003; Flerchinger and Hardegree, 2004; Wang et al., 2004; Hardegree, 2006). These models can be developed for different environmental conditions and different agricultural crops and can be used for accurately forecasting long term crop responses (Probert, 1992).

Cucurbits are warm climate crops which are both cold weather and frost sensitive and most of them require relatively high temperatures for germination (Nerson, 2007). Minimum and maximum germination temperatures have been reported from 15 to 45°C, respectively, with large differences among cultivars (Singh, 1991). Optimum germination temperatures ($T_o$) range from 20 to 32°C; while 15 and 38°C are the minimum and maximum germination temperature, respectively (Milani et al., 2007).

In the preceding context, the objective of the current study was to predict the germination percentage (GP) and germination speed (GS) of some cucurbit vegetable crops (watermelon, melon, cucumber, summer squash, pumpkin and winter squash) by adapting a mathematical model based on temperature.

## MATERIALS AND METHODS

### Seed materials

One-year-old seeds of watermelon (*Citrullus lanatus* (Thunb) Matsum. and Nakai cvs. Amazon $F_1$, Sangria $F_1$ and Farao $F_1$), melon (*Cucumis melo* L. cvs. Galia $F_1$, Kırkagac-637 and Hasanbey-1), cucumber (*Cucumis sativus* L. cvs. Beith Alpha $F_1$ and Bafra), summer squash (*Cucurbita pepo* L. cvs. Urfa and Sakız-5801), pumpkin (*Cucurbita moschata* Duchesne ex Poir. cv. Bafra) and winter squash (*Cucurbita maxima* Duchesne ex Lam. cv. Bafra) were used. Open-pollinated cultivars (Kırkagac-637, Hasanbey-1 and Sakız-5801) and $F_1$ cultivars (Amazon $F_1$, Sangria $F_1$, Farao $F_1$, Beith Alpha $F_1$ and Galia $F_1$) purchased and local populations (Urfa and Bafra) were selected and self-pollinated for two years to reduce genetic variability.

### Germination Test

Germination tests were performed in darkness in a temperature controlled plant growth cabinet pre-set to 12 different temperatures (12, 15, 18, 21, 24, 27, 30, 33, 36, 39, 42 and 45°C). Firstly, the seed surfaces were disinfected with ethanol (70%) for a minute and rinsed with distilled water four times to minimise microorganism development at the early stages of germination. Afterwards, 100 seeds were sprinkled on round filter papers (Watman No. 1) in a 9 cm Petri dish and covered by another filter paper, according to between papers (BP) technique (Anon., 1996). Treatments were arranged in completely randomized design (seed lots within each temperature regime) with three replications. As some cucurbits (squash, pumpkin, and winter squash) had larger seeds, seed plots were divided into 4 subgroups (each Petri dish contained 25 seeds) for each replication to ensure homogenous germination conditions. Ten millilitres of distilled water was added to each Petri dish and the filter papers were regularly moistened to ensure saturation throughout the germination tests. 2 ml of 0.2% Maxim XL was added to the water in each Petri to prevent fungal contamination. Seeds were considered germinated when the radicle protruded at least 2 mm from the seed coat (Jeffrey et al., 1987). Germinated seeds and rotted seeds were counted and discarded at 24 h intervals until no germination occurred on 4 consecutive days (Samimy et al., 1987). GP and GS percentage and index value were evaluated, respecttively. Index value was calculated according to the formula (Sehirali, 1991):

$$GS = \frac{S_1}{D_1} + \frac{S_2}{D_2} + \ldots\ldots\ldots\ldots + \frac{S_n}{D_n}$$

Where, S = number of seeds germinating per day, D = number of days and n = number of seeds and days to final observation.

### Model development procedure

A model, D = [$a - (b \times T) + (c \times T^2)$], developed by Uzun et al. (2001), was adapted for some cucurbits seeds (watermelon, melon, cucumber, summer squash, pumpkin and winter squash) to predict the germination percentage (GP) and germination speed (GS) by carrying out multi-regression analysis in Excel 7.0 computer program. In the model, “D” represented the time (day), “T”, the mean temperature (°C) and “a, b and c” were the coefficients. The rate of variation in seed germination was obtained from the derivative of the above equation

$$Dd/dt = - b + (2 \times c \times T)$$

If the rate of variation is zero, another equation determining optimum temperature ($T_o$) for germination can be obtained. Hence, the equation turns to be

$$T_o = - b / 2 \times c.$$

By employing these stages of the model, optimum germination temperature was determined. Standard equations predicting GP and GS for each crop were also produced. For reference purposes, the optimum temperatures predicted by equations from the present study were compared with those reported in the literature.

## RESULTS

### The effect of temperature on GP and GS

All the cucurbit seeds germinated, to a greater or lesser extent, at the minimum temperature ($T_m$) (12°C), with the exception of watermelon seeds, which commenced germination at 15°C (Figure 1). GP ranged from 9.3% in melon (Galia $F_1$) to 89.3% in summer squash (Urfa) at 12°C, respectively. GP values were the highest in summer squash cv. Urfa (89%), melon cv. Hasanbey-1 (76%) and pumpkin (75%) at 12°C. Moreover, GS values ranged from 0.82 (melon cv. Galia $F_1$) to 8.88 (pumpkin) at 12°C (Figure 2). Local populations and open pollinated cultivars showed higher GP and GS values than hybrids ($F_1$)

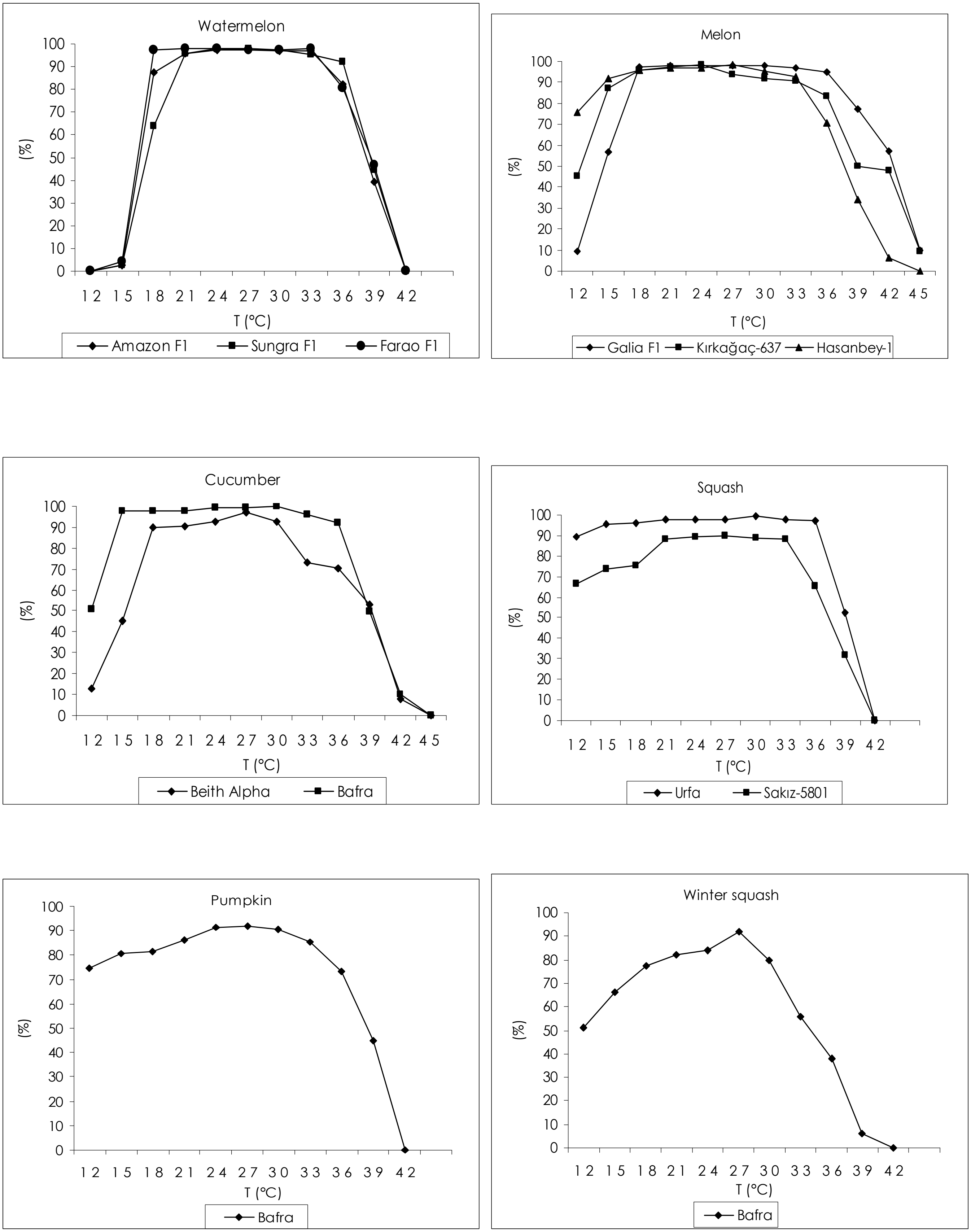


**Figure 1.** Relationship between temperature (°C) and observed germination percentage (GP) (%) for cucurbit vegetable crops.

at $T_m$. Average optimum temperatures ($T_o$) were 24 - 27°C in watermelon and melon, 27°C in pumpkin and winter squash, 27 - 30°C in cucumber and summer squash for GP (Figure 1) and 27°C in summer squash, pumpkin and winter squash, 27-30°C in cucumber, 30°C in watermelon and melon for GS (Figure 2). Germination of cucumber and melon seeds was greatly suppressed at 42°C (8-10%) and 45°C (9-10%), respectively. Besides, germination was not observed at 42°C in watermelon, summer squash, winter squash and pumpkin seeds.

**Prediction of ($T_o$) for GP and GS and model validation**

In determining the adapted seed germination model for each cucurbit, multi- regression analyses were conducted until lower standard errors of independent variables (T and $T^2$), and higher regression coefficient ($R^2$) values of the equations were obtained. From the modelling process, the predicted germination percentages (%) and germination speeds are given in Tables 1 and 2. The relationships between the observed and predicted GP and GS, based on mean temperatures, were also determined (Figures 3 and 4). Predicted GS temperatures were higher than GP temperatures for the assessed cucurbits. The $R^2$ from the new equations for the assessed cucurbits ranged from 0.87 (melon and cucumber) to 0.92 (pumpkin) for GP and from 0.76 (pumpkin) to 0.91 (watermelon) for GS. The optimum temperatures (°C) predicted by the present model ranged from 21.6 (summer squash cv. Urfa) to 27.8 (watermelon cv. Amazon $F_1$) for GP and from 25.5 (winter squash) to 30.4 (melon cv. Hasanbey-1) for GS. The average optimum temperatures (°C) for GP and GS were 25.9 and 29.2 in melon, 26.5 and 28.1 in cucumber, 23.5 and 26.9 in summer squash, 25.0 and 26.4 in pumpkin and 25.3 and 25.5 in winter squash, respectively.

## DISCUSSION

GP and GS increased more or less linearly with increasing temperature at the sub-optimal temperature range (temperatures between $T_m$ and $T_o$) and decreased more or less linearly with increasing temperature at the supra-optimal temperature range (temperatures between $T_o$ and $T_M$) (Figures 1 and 2).

Results indicated that minimum ($T_m$), optimum ($T_o$) and maximum ($T_M$) germination temperatures varied among species and cultivars. The local cultivars (Urfa and Bafra) and open pollinated cultivars (Kırkagac-637, Hasanbey-1 and Sakız-5801) gave higher GP and GS values than hybrid ($F_1$) cultivars at minimum germination temperature (12°C), because of having larger or heavier seeds. Large seeds in this study had higher GP and GS than smaller seeds at $T_m$. Larger or heavier seeds germinated faster than smaller or lighter seeds especially at lower temperatures, which are consequences of thermal dynamics; higher cold tolerance, maintenance of higher energy and nutrient reserves. This result gave a more efficient respiratory conversion, accumulation of more thermal time units than in small seeds under the same temperature regime and subsequently, faster germination (Wang, 2005). Bushy bird nest type melons have relatively large seeds that germinate more quickly and in much higher percentages at 15°C than seeds of other cultivars (Robinson and Decker-Walters, 1997). For these reasons, large seeds have distinct advantages at low seed bed and soil temperatures which enable early seedling emergence in the growing season.

Low GP at low temperature has been reported in cucumber at 14°C (Hegarty, 1973) and the GS of 203 cucumber lines and cultivars varied widely (3.5 to 17.3 days to germination) at 15°C, but not at 20°C (Wehner, 1982). Cucumber seeds germinated rapidly at 20°C, but the time to 50% germination at 14°C decreased substantially and below 11°C, only a small percentage of the seeds germinate (Nienhuis et al., 1983). Lower et al. (1982) showed that there were differences among cucumber cultivars for germination speed at temperatures between 14 and 17°C and Zhuhu and Oijie (1997) determined that a heritable character influenced the germination of cucumber varieties at low temperatures. Moreover, Nilsson (1968) found genetic variation for germination among cultivars at 12, 14, 17 and 23°C in cucumber. Minimum germination temperatures of cucumber were from 11.7 to 15.0°C (Roeggen, 1987).

For GP, optimum temperatures ($T_o$) were relatively higher in summer squash and cucumber seeds (27-30°C) than in watermelon, melon, pumpkin and winter squash seeds (24-27°C). GS values were higher than GP, such that melon seeds germinated faster from 30 - 33°C, but the other cucurbit species gave higher GS from 27-30°C. It was very clear that cucurbit seeds require relatively high temperatures for successful germination and seedling emergence (Hegarty, 1973). Optimum germination temperature for watermelon was around 25 - 28°C (Demir and Mavi, 2004). Optimum soil temperature for germination of watermelon seed ranged from 21.3 to 35.3°C; 15.7°C was the minimum germination temperature (Lorenz and Maynard, 1980). Optimal germination of the cultivar 'Sugar Baby' was in the range of 15 - 35°C (Sachs, 1977). Triploid watermelon seeds germinated poorly at suboptimal temperatures (15°C) (Yang and Sung, 1994). Temperatures between 21 and 35°C were regarded as optimal for germination (Molinar et al., 2004) and minimum and maximum germination temperatures of 12.5 and 35°C were reported for summer squash, respectively (Zehtab-Salmasi, 2006).

In the present study, maximum thermal limits ($T_M$) were 39°C for watermelon, summer squash, pumpkin and winter squash, 42°C for cucumber and 45°C for melon. High temperatures had negative effect on GP and GS and germination ability decreased or ended sharply at maximum temperatures ranging from 42 to 45°C, which is related to the denaturing of proteins, membrane dys-

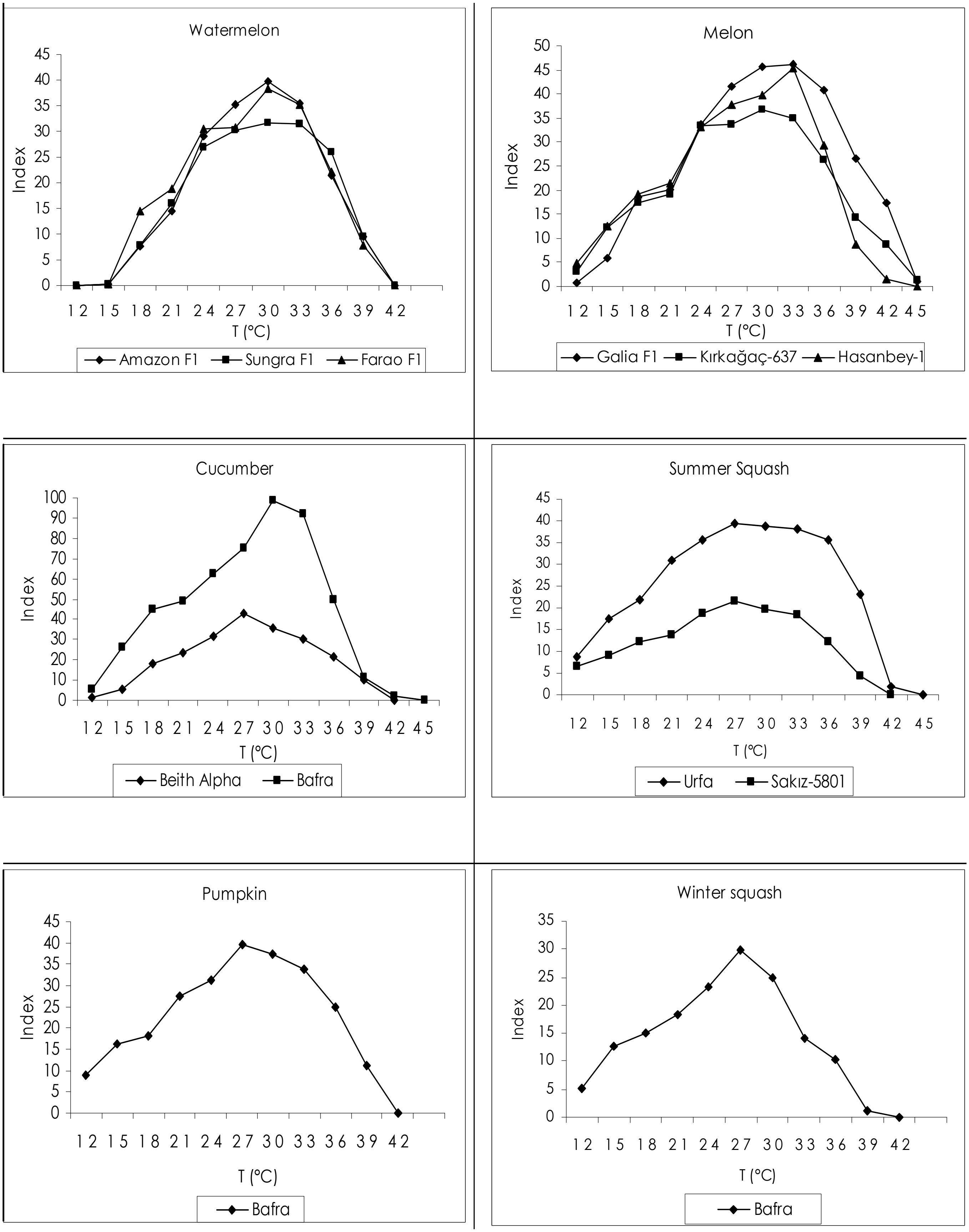


**Figure 2.** Relationship between temperature (℃) and observed germination speed (GS) (Index value) for cucurbit vegetable crops.

**Table 1.** The coefficients a, b and c for the model, [*a - (b x T) + (c x $T^2$)*], their standard errors (SE) and $R^2$ values of the new produced equations predicting germination percentage (GP) (%) based on temperature for some cucurbits.

| Species | Cultivars | Coefficients | | | $R^2$ | Optimum temperatures ($T_o$) (°C) | |
|---|---|---|---|---|---|---|---|
| | | a | b | c | | Predicted by the model | Indicated in literatures |
| Watermelon | Amazon $F_1$ (SE) | -291.23 (12.53)*** | 28.92 (0.96)*** | -0.52 (0.01)*** | 0.91 | 27.81 | 25 - 30 |
| | Sungra $F_1$ (SE) | -290.14 (12.53)*** | 28.82 (0.96)*** | -0.52 (0.01)*** | 0.91 | 27.71 | |
| | Farao $F_1$ (SE) | -289.05 (12.53)*** | 28.70 (0.96)*** | -0.52 (0.01)*** | 0.91 | 27.60 | |
| Melon | Galia $F_1$ (SE) | -61.30 (10.72)*** | 12.60 (0.75)*** | -0.25 (0.01)*** | 0.88 | 25.20 | 25 - 30 |
| | Kırkagaç-637 (SE) | -62.45 (10.72)*** | 12.96 (0.75)*** | -0.25 (0.01)*** | 0.88 | 25.92 | |
| | Hasanbey-1 (SE) | -66.60 (10.72)*** | 13.32 (0.75)*** | -0.25 (0.01)*** | 0.88 | 26.64 | |
| Cucumber | Beith Alpha (SE) | -127.01 (14.04)*** | 16.74 (0.99)*** | -0.32 (0.01)*** | 0.87 | 26.16 | 25 - 30 |
| | Bafra pop. (SE) | -112.09 (14.04)*** | 17.18 (0.99)*** | -0.32 (0.01)*** | 0.87 | 26.84 | |
| Summer Squash | Urfa pop. (SE) | -30.28 (12.45)*** | 10.36 (0.88)*** | -0.24 (0.01)*** | 0.89 | 21.58 | 20 - 25 |
| | Sakız-5801 (SE) | -43.97 (12.45)*** | 12.22 (0.88)*** | -0.24 (0.01)*** | 0.89 | 25.46 | |
| Pumpkin | Bafra pop. (SE) | -35.77 (13.16)*** | 11.48 (0.99)*** | -0.23 (0.01)*** | 0.92 | 24.96 | 20 - 25 |
| Winter Squash | Bafra pop. (SE) | -23.79 (17.73)*** | 10.11 (1.33)*** | -0.20 (0.02)*** | 0.92 | 25.28 | 20 - 25 |

***Significant at the level of $p < 0.001$.

function and finally the termination of metabolic activity (Bradford, 2002; Thygerson et al., 2002).

The current findings were also in accordance with those reported by other workers. Minimum, optimum and maximum germination temperatures were 10, 25 - 30 and 40°C for cucumber and melon, 10, 20 - 25 and 35°C for *Cucurbita* sp. and 10, 25 - 30 and 35°C for watermelon, respectively (Salk et al., 2008). The relationships between the observed GP and GS in the current study and those predicted by the equations generated by this study, were also investigated to establish the equations prediction performance. The coefficients of the solid line were from 0.87 to 0.92 for GP and from 0.76 to 0.91 for GS (Figures 3 and 4). The effect of temperature on GP and GS was much more important and the $R^2$ values were generally high. It was suggested that reliable equations, using temperature to predict GP and GS, be obtained in the present study. It was also possible to determine optimal temperatures ($T_o$) for GP and GS by using the coefficients of the independent variables (a, b and c) obtained from the equations (Tables 1 and 2). When the predicted optimum temperatures for GP in the present study were compared with those from the literature (Table 1), there was generally a high agreement, although it was not possible to find optimum temperatures in the literature for GS (Table 2).

Models such as those predicting days to germination or optimum temperatures may be used to determine proper timing for seed sowing in different regions and to utilize the vegetative growth period of these regions more

**Table 2.** The coefficients a, b and c for the model, [*a - (b x T) + (c x $T^2$)*], their standard errors (SE) and $R^2$ values of the new produced equations predicting germination speed (GS) (Index value) based on temperature for some cucurbits.

| Species | Cultivars | Coefficients | | | $R^2$ | Optimum temperatures ($T_o$) (°C) | |
|---|---|---|---|---|---|---|---|
| | | a | B | c | | predicted by the model | indicated in literatures |
| Watermelon | Amazon $F_1$ (SE) | -128.06 (5.55) *** | 10.96 (0.40)*** | -0.19 (0.007)*** | 0.91 | 28.85 | NA |
| | Sungra $F_1$ (SE) | -127.81 (5.55)*** | 10.94 (0.40)*** | -0.19 (0.007)*** | 0.91 | 28.80 | |
| | Farao $F_1$ (SE) | -127.56 (5.55)*** | 10.92 (0.40)*** | -0.19 (0.007)*** | 0.91 | 28.74 | |
| Melon | Galia $F_1$ (SE) | -87.09 (14.93)*** | 8.51 (0.37)*** | -0.15 (0.006)*** | 0.84 | 28.37 | NA |
| | Kırkagaç-637 (SE) | -88.73 (14.93)*** | 8.67 (0.37)*** | -0.15 (0.006)*** | 0.84 | 28.91 | |
| | Hasanbey-1 (SE) | -90.37 (14.93)*** | 9.13 (0.37)*** | -0.15 (0.006)*** | 0.84 | 30.44 | |
| Cucumber | Beith Alpha (SE) | -136.48 (14.93)*** | 12.15 (1.06)*** | -0.22 (0.01)*** | 0.80 | 27.62 | NA |
| | Bafra pop. (SE) | -113.63 (14.93)*** | 12.54 (1.06)*** | -0.22 (0.01)*** | 0.80 | 28.50 | |
| Summer Squash | Urfa pop. (SE) | -46.27 (5.71)*** | 5.93 (0.40)*** | -0.11 (0.006)*** | 0.86 | 26.20 | NA |
| | Sakız-5801 (SE) | -58.33 (5.71)*** | 6.05 (0.40)*** | -0.11 (0.06)** | 0.86 | 27.51 | |
| Pumpkin | Bafra pop. (SE) | -71.62 (9.89)*** | 7.40 (0.78)*** | -0.14 (0.14)** | 0.76 | 26.43 | NA |
| Winter Squash | Bafra pop. (SE) | -59.97 (5.65)*** | 6.65 (0.47)*** | -0.13 (0.09)** | 0.89 | 25.50 | NA |

**Significant at the level of $p < 0.01$; ***Significant at the level of 0.001; NA = Data not available.

productively. They can also assist seedling producers in preseason and inseason management decisions related to cultural practices and also decisions made under different climatic regimes and for different requirements. However, it should be taken into consideration that most germination models are generated and modified in the laboratory under controlled environmental conditions and that relatively few reports are available for field conditions (Finch-Savage et al., 2000; Hardegree and Van Vactor, 2000; Hardegree et al., 2003; Wang, 2005). Seedling emergence under field conditions is determined by more complex interactions of weather conditions, soil, seed and seedling characteristics. Extreme seedbed conditions, such as soil impedance and reduced oxygen supply can have considerable effects on seedling emergence as a result of seed deterioration and seedling mortality (Kolb et al., 2002).

## Conclusion

Considering that there has been marked interest by many workers in modelling plant growth and development in recent years, the equations produced in the present study may contribute usefully to this field. The temperature limits (12 to 45°C) used in the present study enabled the

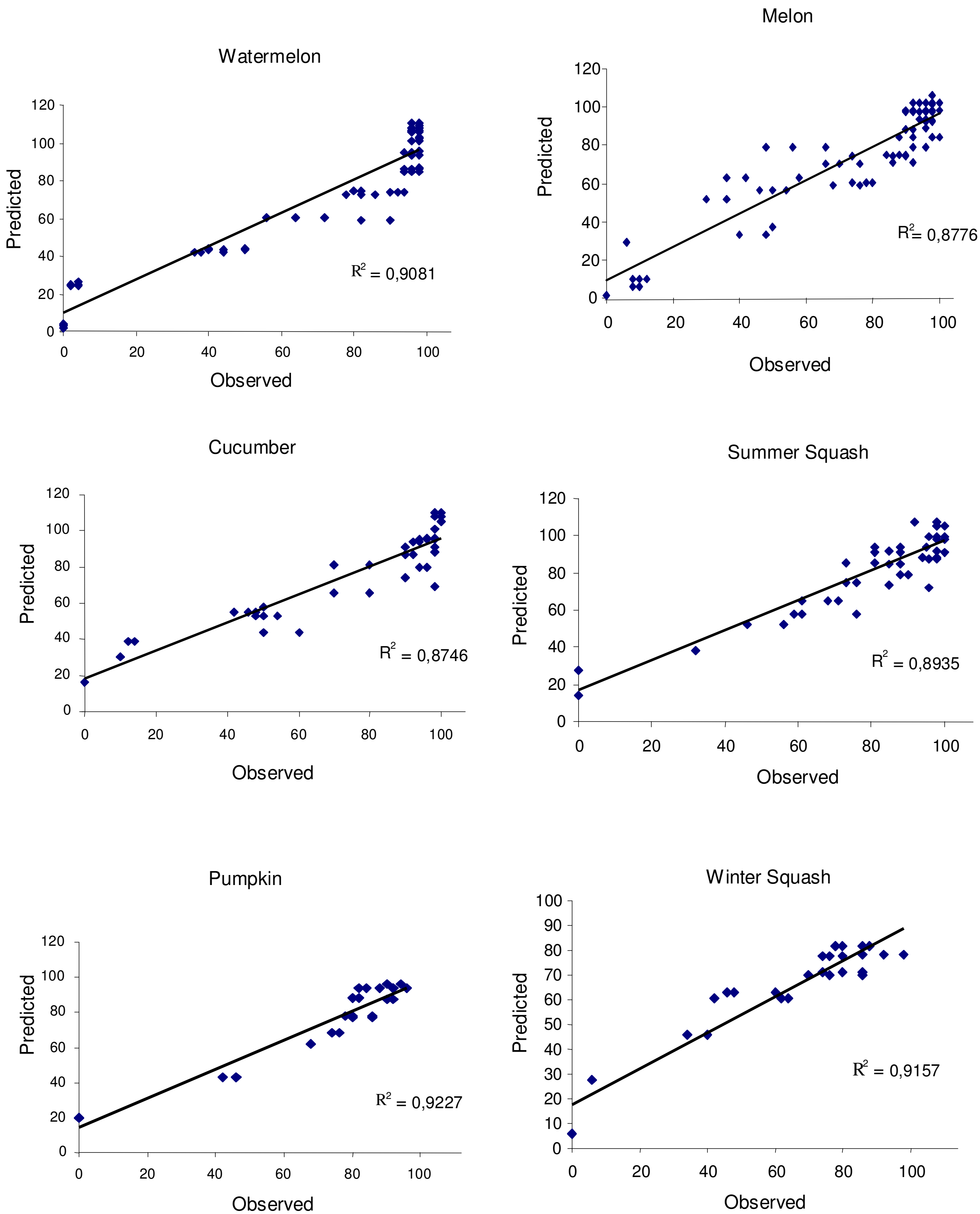


**Figure 3.** Relationship between observed and predicted germination percentage (GP) (%) for cucurbit vegetable crops.

generated model to be used confidently for the studied cucurbits. The model also complements earlier models predicting plant growth, development and yield and it can be further validated and evolved by other modellers.

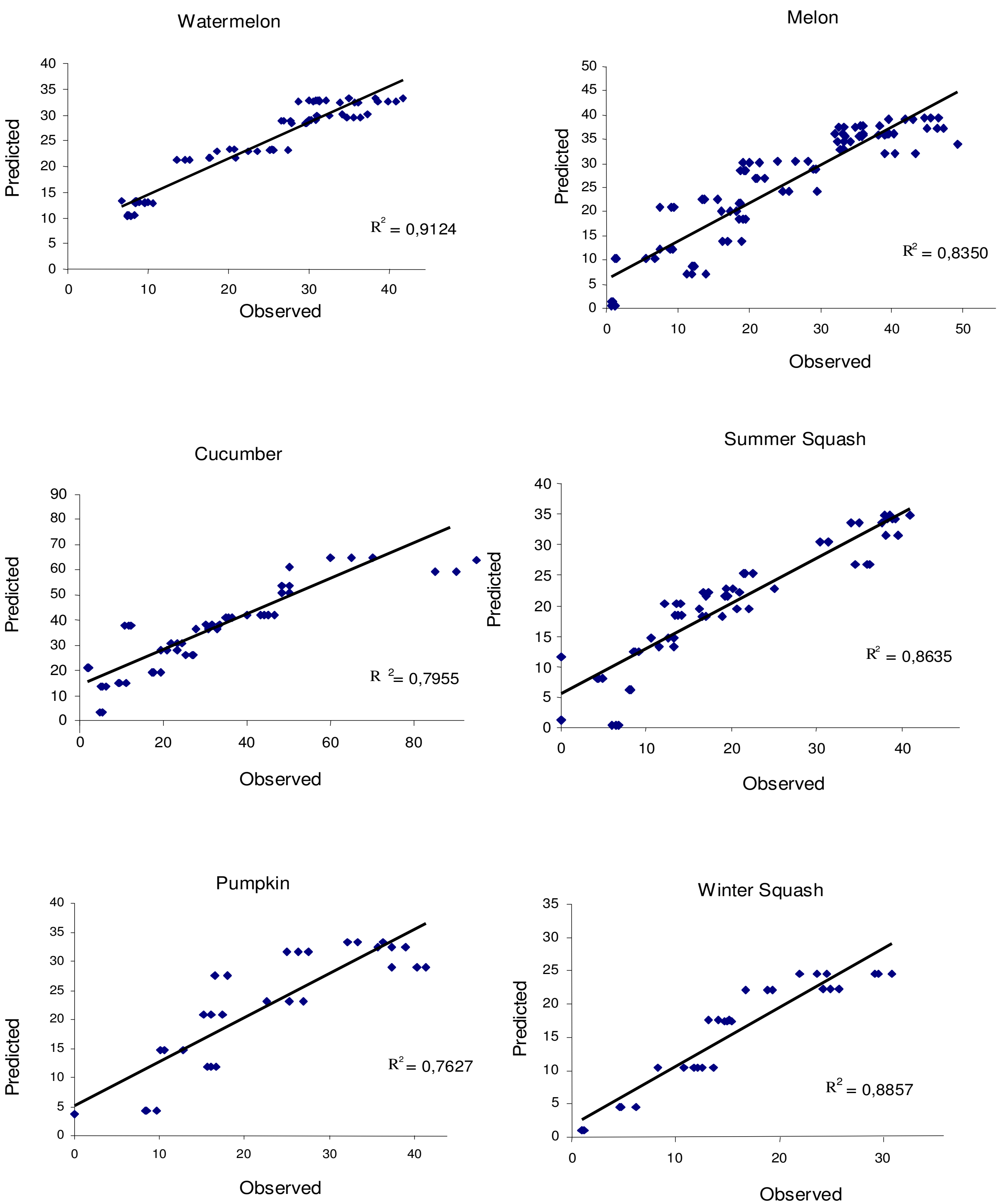


**Figure 4.** Relationship between observed and predicted germination speed (GS) (Index value) for cucurbit vegetable crops


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