# Use of Models as Non-destructive Method for Leaf Area Estimation in Horticultural Crops

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# Use of Models as Non-destructive Method for Leaf Area Estimation in Horticultural Crops

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**ABSTRACT**

*Leaf area estimation is an important biometrical trait for evaluating leaf development and plant growth analysis in field study of horticultural as well as other species of crop plants. These measurements can be made either destructively and/or non-destructively by using a variety of sensitive instruments as well as models of leaf area estimation. Easy, accurate, cost-effective, and nondestructive methods of leaf area estimation are useful tool in physiological studies related to plant growth and development. The use of regression equations is a nondestructive, simple, quick, accurate, reliable and not expensive method of leaf area estimation. The usual procedure of this method involves measuring length (L), breadth (W) and/or dry mass (M) of a sample of leaves and then calculating the several possible regression coefficients or leaf factors to estimate the area of subsequent leaf samples. Computer programs such as Excel, SAS and SPSS may be used in this process. The paper thrashed out several leaf area estimation models of horticultural crops from the available literature and synthesized in tabular form for the use of researchers. Article also offered some advantages and disadvantages of leaf area estimation models used for analyzing the plant growth and development.*

## INTRODUCTION

Crop growth, productivity and quality are directly related to leaf area (LA) as leaves constitute the most important aerial organ of the plant, playing a major role in the photosynthetic assimilation by means of the light absorbing pigments (*e.g.*, chlorophyll and carotenoids), which they possess in abundance. Hence, the total leaf area, which in the majority of cases has a direct bearing on the amount of chlorophyll, is an important parameter for assessing the ability of the plant to synthesize its dry matter (Prasada Rao *et al*., 1978). In addition, leaf area development strongly influences water and nutrient use of the horticultural crop plants and thus important for cultural management practices such as irrigation, fertilization, etc. It is also needed for evaluation of training and pruning systems and estimation of pest population densities in horticultural crops (Lang, 2005a; Anderson *et al*., 1999; Sepulveda and Kliewer, 1983; Elsner and Jubb, 1988; Lang, 2000b). A large number of methods, either destructive or not, have been developed to measure leaf area. However, measuring the surface area of a large number of leaves, especially in the field, can be costly, time consuming, laborious and usually destructive (Beerling and Fry, 1990). Many methods like tracing, blueprinting, photographing, or using a conventional planimeter, require the excision of leaves from the plants. It is therefore, not possible to make successive measurements of the same leaf. Also, the plant canopy is damaged, which might cause problems to other measurements or experiments (Lu et al., 2004). Non-destructive methods, which do not require the leaves to be detached, are useful because they allow measurements to be repeated during the plant's growth period, and reduce the variability associated with destructive sampling procedures (Silva *et al*., 2005; Pandey and Singh 2011). Instruments and laser optic apparatuses have been developed for quick, accurate, and non-destructive measurement of leaf area (Daughtry 1990; Fladung and Ritter, 1991; Mori *et al*., 1991; Smith *et al*., 1991; Blanke, 1995; Ebert, 1995; Beverly and van Lersel, 1998; Igathinathane *et al*., 2006). However, these devices are somewhat expensive, time-consuming and complex (Manivel and Weaver, 1974; Robbins and Pharr, 1987) for basic and simple studies. A modelling approach involving linear relationships between LA and one or more dimensions of the leaf is an inexpensive, rapid, reliable and a nondestructive alternative for accurately measuring LA (Williams and Martinson, 2003; Lu *et al*., 2004). Thus for many fruit (Kobayashi, 1988; Potdar and Pawar, 1991; Uzun and Çelik, 1999; Campostrini and Yamanishi, 2001; Williams and Martinson, 2003; Demirsoy *et al*., 2004; Demirsoy *et al*., 2005; Wu *et al*., 2010; Moghaddam, 2014), vegetables (Chien and Lin. 2002; Blanco and Folegatti, 2005; Carmassi *et al*., 2007; Olfati *et al*., 2010; Cemek *et al*., 2011; Hinnah *et al*., 2014; Tanko and Hassan, 2016), ornamental (Pereyra et al., 1982; Barbieri et al., 1994; Pinto *et al*., 2004; Carmassi *et al*., 2007; Fascella *et al*., 2013) and medicinal (Cirak *et al*., 2005; Zenginbal *et al*., 2006; Antunes, *et al*., 2008; Odabas *et al*., 2009; Dheebakaran and Jagannathan, 2009) plants non-destructive and easily applied models for LA estimation have been developed based on simple measurements of leaf length, width, and dry mass. This indirect non-destructive method can provide accurate leaf area estimates *in situ*. The objective of this article was to offer handy simple, accurate, non-destructive and time saving leaf area prediction models for various crop species to be used by the researchers working in the field of horticultural sciences.

## MATERIALS AND METHODS

In general, the development of an estimation model of leaf area requires the measurement of the actual area of each leaf and, often, multiple regressions with length and /or width, etc. Common parameters for prediction equations are leaf length, leaf width, leaf dry mass, petiole length, or some combination of these variables (Gamiely *et al*., 199; Pandey and Singh, 2011; Rouphael et al, 2010a; Pandey and Singh, 2011). Many studies have been carried out with linear leaf measurements that are highly correlated with leaf area in fruits (Fallovo *et al*., 2008; Demirsoy, 2009), vegetables (Hinnah *et al*., 2014; Tanko and Hassan, 2016), ornamentals (Barbieri *et al*., 1994; Fascella *et al*., 2013) and medicinal plants (Kumar, 2009; Zhang and Liu, 2010; ). Computer programs such as Excel, SAS and SPSS may be used in this process. For example, for a typical method, each leaf should be placed on a sheet of paper and be photocopied. Then, to measure the actual leaf area, a digital leaf area meter or any suitable tool may be used. The leaf width (W) and length (L) of the leaves sampled can be measured by a simple ruler. After this, regression analysis of the data may be performed separately for each genotype, species or cultivar. The analysis can be conducted with various subsets of the independent variables; for instance, leaf length, leaf width, 'leaf length'$^2$ ($L^2$), 'leaf width'$^2$ ($W^2$) and the [$L^2$ / $W^2$] ratio to develop the best model for predicting leaf area. Regression analyses should be carried out until the deviation sum of squares is minimized. To choose the best model, standard error, coefficient of correlation ($r^2$), probability and F values of the proposed model are considered. In addition, representative leaf samples should be used to increase reliability of the model. Samples consisting of leaves of different sizes should be used to produce an accurate leaf area estimation equation. Otherwise, the equation will probably be unreliable. As measurement of the leaf area of plants such as grapevine is more complicated than for plants such as the peach tree, more samples are therefore required to produce an accurate model. Ackley *et al.* (1958) also noted calculations of the minimum number of leaves to provide a reliable linear measurement to area conversion modeling equation. So, any proposed model should be validated with independent data before being used for experiments. The use of a validated estimation model of leaf area is straightforward and saves time. However, developing a new leaf area model can be time-consuming, lasting for up to three months. For example, a large number of leaf samples of varying sizes can be collected, either from an orchard at different periods or, when leaves reach the desired size, from an orchard at one time.

## REGRESSION MODELS FOR SPECIFIC HORTICULTURAL CROPS

### *Fruit Crops*

Several leaf area prediction models for fruit species developed in previous studies are presented in table 1. Studies indicated that leaf area in the Stuart pecan can be estimated with reasonable accuracy and rapidity by employing the relationship of leaf area per terminal to terminal length (Sparks, 1966; Smith, 1992). A logarithmic model for nondestructive estimation of leaf area in cacao has also been developed by Reynolds (1971). A leaf area estimation model with high degree of correlation coefficient (0.961) has also been established by Kobayashi (1988) in guava. The length of the midrib, petiole and maximum width of the lamina in sour orange leaves were used to develop leaf area prediction models which exhibited a good predictive ability as indicated by $r^2$ value of 0.93 (Ramkhelawan and Brathwaite, 1990). Using simple measure of leaf length and width, a nondestructive and cost effective measure for leaf area estimation of rabbit-eye blueberries was presented by NeSmith (1991). A strong correlation ($r^2$ = 0.96-0.98) between LA and various combinations of leaf length (L) and width (W) in certain cultivars of banana has been reported which can be exploited for prediction of leaf area in these fruits (Potdar and Pawar, 1991). Leaf area estimation model has also been offered for white mulberry (Satpathy, *et al*., 1992) with good correlation value ($r^2$ = 0.960). Simple leaf area estimation equations have also been developed (Panta and NeSmith, 1995; Wu *et al*., 2010) for musk melon that offers reliable prediction of leaf area across several cultivars. By means of measuring leaf length (L) and width (W) Uzun and Celik

(1999) achieved excellent equations for estimation of leaf area in avocado, grapes, kiwifruit, lotus plum, raspberry and red currant fruits. All models produced a coefficient of determination ($r^2$) equal to or greater than 0.966. The length of midrib and the maximum width of lamina were used to develop non-destructive leaf area prediction models ($r^2$ = 0.997) in definite pistachio genotypes (Ranjbar an Damme, 1999). Models with high degree of correlation coefficients ($r^2$ = 0.983, 0.985) are also available for leaf area estimation in kiwifruits (Uzun and Celik, 1999; Williams and Martinson, 2003; Mendoza-de Gyves *et al*., 2007). Using the central vein length of papaya leaf Campostrini and Yamanishi (2001) were able to develop a logarithmic equation ($r^2$ =0.898) for assessment leaf area in papaya.

Studies on strawberry offered some reliable equations that predicts leaf area non-destructively by linear measurements of leaf geometry (Mandal *et al*., 2002 - $r^2$ = 0.993; Demirsoy *et al*., 2005 - $r^2$ = 0.991). Studies were also undertaken to generate suitable equations for nondestructive reliable estimation of leaf area in various cultivars of sweet cherry (Demirsoy and Demirsoy (2003a and 2003b; Cittadini and Peri, 2006; Demirsoy and Lang, 2010). In order to estimate the individual leaf area in custard apple Silva *et al*. (2004) were able to produce a plain equation with significant correlation value ($r^2$ = 0.770). A model for predicting the leaf area ($r^2$ = 0.998) was developed for peach by measuring lamina width, length and leaf area and the model was validated by measuring leaf samples of different peach trees (Demirsoy *et al*., 2004). An equation for estimating the leaf area in chestnut varieties was also derived ($r^2$ = 0.988) by measuring the lamina width, length and leaf area (Serdar and Demirsoy, 2006). Using linear measurements of leaf length (L), width (W) and LA a simple equation was developed ($r^2$ = 0.982) for estimating leaf area in Hazelnut trees (Cristofori *et al*., 2007).

Fallovo *et al*. (2008) developed several models that could be used conveniently for estimating leaf area in small fruits (blackberry, gooseberry, blueberry, raspberry and redcurrent) with high $r^2$ values (0.974 – 0.986). Cristofori *et al*. (2008) brought a simple equation ($r^2$ = 0.890) for analyzing the photosynthetic surface area accurately in persimmon. Odabas *et al*. (2009) developed a leaf area model for cherry laurel with significant $r^2$ value (0.95). Mazzini *et al*. (2010) derived an easy leaf area prediction model ($r^2$ = 0.997) for citrus trees. Rouphael *et al*. (2010a) suggested that length-width (L × W) model can provide more accurate estimations of watermelon leaf area across cultivars than those based on single length (L) or width (W) measurement. Ghoreishi *et al*. (2012) provided a regression equation ($r^2$ = 0.865) for analyzing the leaf area in mango seedlings. Using a leaf area meter (Moghaddam, 2014) developed two linear models which were found as most accurate estimates for estimation of leaf area in Red ($r^2$ = 0.94) and Golden ($r^2$ = 0.98) delicious apples. Looking for an appropriate leaf area estimation equation in grapes various studies (Elsner and Jubb, 1988; Uzun and Celik, 1999; Montero *et al*., 2000; Williams and Martinson, 2003; Buttaro *et al*., 2015) customized a range of models with high degree of correlations ($r^2$ = 0.963 to 0.994.) that can be used for nondestructive prediction of leaf area.

***Vegetable crops***

Leaf area prediction models for vegetables crops developed in previous studies are presented in table 2. Regression equations for inference of leaf area in summer squash (NeSmith, 1992), radish (Salerno, *et al*., 2005), faba bean (Peksen, 2007), green pepper (Ray and Singh 1989; De Swart, *et al* 2004; Cemek *et al*., 2011) and onion (Córcoles *et al*., 2015) are validated with strong correlation coefficient values. Kintomo and Ojo (2000) reported that a strong correlation existed between leaf area and various combinations of leaf length (L) and width (W) in grain amaranth (*Amaranthus cruentus* L). Regression models are presented for LA prediction in each cultivar. Chien and Lin (2002) presented leaf area prediction models for edible amaranth ((*A. mangostanus* Linn.) and (*A. inamoenus* Willd*)*, broccoli, cabbage and Chinese cabbage using elliptical hough transform. Various available models with regard to broccoli (Chien and Lin, 2002; Stoppani *et al*., 2003; Olfati *et al*., 2010) and cabbages (Chien and Lin, 2002; Olfati *et al*., 2010) with précised degree of correlation ($r^2$ = 0.869 – 0.993 and $r^2$ = 0.985 – 0.953) presented striking opportunity of leaf area estimation in these crops.

Leaf area estimation through models as nondestructive means were attempted in cowpea, cucumber, okra as well as in tomato by previous workers (Blanco and Folegatti, 2003; Blanco and

Folegatti, 2005: Carmassi *et al*., 2007: Tanko and Hassan, 2016) and predictive equations have been provided with good levels of significance ($r^2$ = 0.884 – 0.999). Rivera, *et al*., 2007 and Hinnah *et al*. (2014) suggested that for leaf area estimation in eggplant using the product between the linear measurements of length (L) and width (W) of the leaf blade allowed to obtain the satisfactory leaf area of plants nondestructively However, they suggested that quadratic equations with single dimension of length exhibited a high degree accuracy and precision in estimating individual LA of eggplant which also lowered the time of measurement. Regression analyses of LA versus FW, DW, L and W revealed several models for estimating the area of individual basil leaves (Bazaza *et al*., 2011) wherein the models, one based on the sum of dimension squares was found most accurate for Genovese ($r^2$ = 0.895) while the product of dimension squares was the most suitable for Purple Ruffles ($r^2$ = 0.817).

***Ornamental Crops***

The correlation equations between the actual and predicted leaf area as nondestructive mean of leaf area analysis have also been fashioned for certain vegetables crops (Table 3). Barbieri *et al.* (1994) suggested a non-destructive method of leaf area estímation from simple regression equation ($r^2$ = 0.982). Leaf area can also be measured with the help of linear dimensions of leaf in sunflower; however, neither length nor breadth alone gave consistent LA estimation but both length and breadth measurements were needed for precise measurement of leaf area in sunflower (Bange, *et al*., 2000). Regression equations developed for *Zennia elegans* using leaf length and breadth revealed that leaf area prediction can be made accurately for different genotypes of Zennia using prediction models (Pintp *et al*., 2004). Chen and Lin (2004) suggested a nondestructive estimation of leaf area in Phalaenopsis using linear dimensions of leaf with high degree of coefficient correlation ($r^2$ = 0.990). Similarly, Carmassi *et al*. (2007) advocated an empirical relationship between leaf area ans leaf dimensions in gerbera having $r^2$ and RMSE values of 0.910 and 14.71, respectively. Based on the simple L and W measurements, Fascella *et al*. (2009) presented a plain regression equation for leaf area estimation in *Euphorbia* with $r^2$ value of 0.981. A linear model having L×W as the independent variable provided the most accurate estimate ($r^2$ = 0.991; MSE = 0.726) of LA in rose (Rouphael *et al*., 2010b). In order to estimate the leaf area in merremia, De Carvalho *et al*. (2011) described a clear relationship between the LA and dimensions principal, primary and secondary leaflets. Giuffrida *et al*. (2011) found that regression analysis of LA versus L and W or some combinations of these parameters resulted in several models that could be used for estimating the leaf area of individual bedding plants like pot marigold, dahlia, sweet William, geranium, petunia and pansy. They reported that a linear model having LW as the independent variable provided the most accurate estimate (highest $r^2$, smallest mean square error, and the smallest predicted residual error sum of squares) of LA in all bedding plants.

***Medicinal Crops***

Excellent relationships between the different dimensions and actual leaf area have also been reported by various workers in certain medicinal plants (Table 4). Working on nondestructive leaf estimation methods, Odabas *et al*. (2005) achieved some excellent models for estimation of leaf area in some medicinal plants wherein all $r^2$ values and standard errors were found to be significant at the $P < 0.001$ level. To achieve a nondestructive leaf area estimation in summer snowflake Cirak *et al*. (2005b) develops a leaf area prediction model which was significantly correlated ($r^2$ = 0.97) at 0.001 level. A highly significant ($r^2$ = 0.99) leaf area prediction model was also produced for tea (Zenginbal *et al*. 2006). Leaf area prediction can be made in Stevia (sugar plant) either by using leaf area factor of 0.548 or the linear regression equation (Ramesh *et al*., 2007). Antunes *et al*. (2008) were able to establish an allometric model as single power for non-destructive leaf area estimation in coffee with excellent correlation coefficient (r2 = 0.996) and standard error (MSE = 0.0064) values. Odabas *et al*. (2009) accounted a non-destructive leaf area prediction model for "Kiraz" cherry laurel using leaf L, W and LA measurements with $r^2$ value of 0.95.

Several regression models were developed to predict the leaf area for saffron efficiently and nondestructively (Kumar, 2009). In order to develop a nondestructive technique of LA estimation in

Bergenia purpurascens, Zhang and Liu (2010) obtained a regression equation with high degree of correlation coefficient ($r^2$ = 0.950). Cirak *et al*. (2005a) found respectable relationships between leaf area and its different dimensions in selected medicinal plants. Studies revealed that irrespective of stages, the third leaf from the top has high correlation with total leaf area of the horse-eye bean plant. It was further observed that the area of the middle leaflet had significant relationship with total area of trifoliate leaf. The correction factors to find out the total leaf area of a plant from the leaflet area measurements were also worked out Dheebakaran G and Jagannathan R (2009). A linear model having L × W as the independent variables provided the most accurate estimate of leaf area for *Picrorhiza kurroa*, an endangered medicinal plant of Western Himalaya (Kumar and Sharma, 2013). Candido *et al*. (2013) describd a plain equation for estimation of leaf area in bush willows that was having high level of significance ($r^2$ = 0.952). Accurate measure of the leaf area of *Styrax pohlii* and *S. ferrugineus can be made* by using the LA = 0.582+0.683WL and LA = -0.666+0.704WL equations, respectively that exclude the necessity of leaf excisions and/ or expensive equipments (Souza and Habermann, 2014).

## ADVANTAGES AND DISADWANTAGES OF LEAF AREA ESTIMATION MODELS

Models to predict leaf area non-destructively can provide researchers with many advantages in horticultural experiments. The most important advantages are as follows:

1. The models enable researchers to measure leaf area on the same plants during plant growth. The equations allow estimations of leaf growth from bud burst to leaf fall, and they reduce variability since the same leaf is used during the experiment. In addition, destructive leaf area measurements are not possible in many investigations. The use of equations eliminates the need for the detachment of leaves from plants.
2. Reliable models eliminate the need for expensive leaf area meters and labor.
3. Leaf area measurement is easy and quick if a reliable equation is obtained or chosen, thereby saving time.
4. In leaf measurements, consistent results are obtained by reliable equations, although non-consistent results may be obtained by a planimeter, depending upon hand manipulation.
5. Use of the modeling equations costs nothing.

In addition, Reynolds (1971) suggested that, in nutritional studies of young cacao cuttings, it became necessary to develop a rapid method for estimating leaf area. Ramkhelawan and Brathwaite (1990) stated that, in weed control investigations involving container-grown sour orange rootstocks, it became necessary to estimate leaf area by a non-destructive method. Kobayashi (1988) indicated that a rapid non-destructive method for estimating the leaf area of the guava in the field would be useful.

A considerable disadvantage of non-destructive methods is that, if the equation is unreliable, incorrect results may be obtained. To prevent this, leaf samples must be taken at different times and chosen at different sizes while an equation of the leaf area estimation is constructed. In addition, the equation should be tested or evaluated for each leaf at different sizes. Moreover, the obtained equation must be validated by other leaf samples before it is used in any experiment.

## CONCLUSION

Nowadays, computer technology and mathematical modeling are progressing rapidly. These, and other developments, have advanced well. The developments have facilitated and accelerated our scientific studies. Therefore, benefiting from the opportunities is useful and necessary. This study is a mini-review that presents some leaf area estimation models with information regarding the advantages and disadvantage of their usage. Moreover, it gives suggestions about how an accurate mathematical model may be constructed. Most importantly, this mini-review shows that the models produced in previous studies for fruit species can be reliably used.

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## (Tables & Figures)

**Table 1. Useful leaf area estimation models developed through various studies for fruit crops**

| **Common/ scientific name** | **Variety** | **Model** | **$R^2$** | **Reference** |
|---|---|---|---|---|
| Apple (Malus domestica) | Red Delicious | $LA= 1.01 + 0.82 \times L \times W$ | 0.940 | (60) |
| Apple (Malus domestica) | Golden Delicious | $LA= 1.23 + 0.87 \times L \times W$ | 0.940 | (60) |
| Avocado (Persea Americana L.) | General | $LA = – 50.63 – 1.353\ L / W + 5.347 \times W + 0.6 \times W^2 + 5.489 \times L$ | 0.983 | (94) |
| Banana (*Musa* × *paradisiacal)* | Ardhapuri | $LA = – 0.0334 + 0.8402 \times L \times W$ | 0.960 | (72) |
| Banana (*Musa* × *paradisiacal)* | Basrai | $LA = 0.0266 + 0.7629 \times L \times W$ | 0.980 | (72) |
| Blackberry (Rubus fruticosus L.) | General | $LA = 0.90 + 0.70 \times L \times W$ | 0.975 | (39) |
| Cacao (*Theobroma* cacao) | General | $\log LA = – 0.632 + 1.987 \log L$ | 0.998 | (78) |
| Cherry Laurel (*Laurocerasus officinalis* Roem.) | Kiraz | $LA = (-55.5877) + (19.98318 \times W) + (-0.83723 \times W^2) + (0.143132 \times L^2)$ | 0.950 | (65) |
| Chestnut (*Fagus* castanea) | General | $LA = 3.36 + 0.11\ L2 – 0.26\ (L^2 / W^2) + 1.1 \times W^2$ | 0.988 | (86) |
| Citrus (*Citrus species*) | General | $LA = 0.680\ (L \times W) – 0.103$ | 9.997 | (58) |
| Custard Apple (*Annona squamosa* L.) | General | $LA = 0.72 \times L\ x\ W$ | 0.770 | (87) |
| Gooseberry (*Ribes grossularia* L.) | General | $LA = 0.58 + 0.72 \times L \times W$ | 0.974 | (39) |
| Grape (*Vitis vinifera* L.) | General | $LA = 0.465 + 0.914 \times L \times W$ | 0.981 | (12) |
| Grape (*Vitis vinifera* L.) | Niagara | $LA = 0.637 \times W^{1.995}$ | 0.982 | (95) |
| Grape (*Vitis vinifera* L.) | DeChaunac | $LA = 0.672 \times W^{1.963}$ | 0.963 | (95 |
| Grape (*Vitis vinifera* L.) | Concord | $LA = – 3.01 + 0.85 \times W \times L$ | 0.984 | (38) |
| Grape (*Vitis vinifera* L.) | Isabella | $LA = – 114.43 – 58.48\ L / W + 0.651\ W^2 + 210.86\ (L / W)$ | 0.986 | (94) |
| Grape (*Vitis vinifera* L.) | Narince | $LA = – 114.43 – 65.79\ L / W + 0.651\ W^2 + 210.86\ (L / W)$ | 0.986 | (94) |
| Grape (*Vitis vinifera* L.) | Cencibel | $LA = 0.587 \times L \times W$ | 0.994 | (61) |
| Guava (*Psidium guajava*) | General | $LA = 16.44 – 3.11 \times L + 0.58\ L2$ | 0.961 | (50) |
| Hazelnut (*Corylus avellana*) | General | $LA = 2.59 + 0.74 \times L \times W$ | 0.982 | (25) |

| | | | | |
|---|---|---|---|---|
| Highbush blueberry (*Vaccinium corymbosum* L.) | General | LA = 0.54 + 0.68 × L × W | 0.986 | (39) |
| Kiwifruit (*Actinidia deliciosa* A. Chev.) | General | LA = – 50.63 – 5.412 (L / W) + 5.347 × W + 0.24 × $W^2$ + 5.489 × L | 0.983 | (94, 95) |
| Kiwifruit (*Actinidia deliciosa* A. Chev.) | Hayward | LA = 0.82 (L × W) – 0.28 | 0.985 | (59) |
| Lotus plum (*Prunus domestica)* | General | LA = – 50.63 – 2.706 ( L/ W) + 5.34 7 × W + 0.12 × $W^2$ + 5.489 × L | 0.983 | (94) |
| Mango (*Mangifera indica* L) Seedling | Seedling | LA = 0.2452 (L × W) × N | 0.865 | (44) |
| Muskmelon (*Cucumis melo*) | General | LA = –2.47 + 0.86 (L × W) | 0.98 | (69) |
| Muskmelon (*Cucumis melo*) | Tianhun | LA = 0.67 × L × W | 0.988 | (96) |
| Muskmelon (*Cucumis melo*) | Chioumih | LA = 0.73 × L × W | 0.989 | (96) |
| Muskmelon (*Cucumis melo*) | Zhufen | LA = 0.65 × L × W | 0.994 | (96) |
| Papaya (*Carica* papaya) | General | Log LA = 0.315 + 1.85 Log LLCV | 0.898 | (13) |
| Persimon (*Diospyros kaki L.)* | General | LA = 3.83 + 0.69 × L × W | 0.98 | (24) |
| Peach (*Prunus persica*) | General | LA = -0.5 + 0.23 × L / W + 0.67 × L × W | 0.998 | (33) |
| Pistachio (*Pistacia* khinjuk subsp. oblonga) | General | LA = (L1 x W1) + (L2 x W2) + (L3 x W3) | 0.960 | (76) |
| Pistachio (*Pistacia* mutica subsp. capulica) | General | LA = (W1 + W2 + W3) | 0.980 | (76) |
| Blueberry (*Vaccinium virgatum*) | Rabbiteye | LA = 0.31 + 0.62 × L × W | 0.950 | (64) |
| Raspberry (*Rubus idaeus* L.) | General | LA = 0.03 + 0.71 × L × W | 0.982 | (39) |
| Raspberry – Red (*Rubus idaeus* × *strigosus* | Rubin | LA = – 148.65 – 33.46 LLL + 29.764 ULL + 29.72 LLL | 0.988 | (94) |
| Redcurrant (*Rubes rubrum* L.) | General | LA = 1.72 + 0.69 × L × W | 0.980 | (39) |
| Red currant (*Rubes rubrum* L.) | General | LA = – 114.43 – 73.1 (L / W) + 0.651 W2 + 210.86 (L / W) | 0.966 | (94) |
| Sour orange (*Citrus aurantium* L) | General | LA = 0.79 + 1.45 × W | 0.930 | (75) |
| Strawberry (*Fragaria* × *ananassa*) | General | LA = 1.89 + 2.145 × upper lobe length × left lobe width | 0.993 | (32) |
| Strawberry (*Fragaria* × *ananassa*) | General | LA = 1.89 + 2.145 × (upper lobe length) × (left lobe width) | 0.993 | (32) |
| Strawberry (*Fragaria* × *ananassa*) | General | LA = 165.91 (X) – 2716.35 or LA = 161.03 (X1) – 2121.8 | 0.951 | (56) |
| Stuart pecan (*Carya illinoensis*) | General | Log LA (for leaflet) = – 0.3088 + 1.6990 log (midrib length)<br>LA per terminal = 192.0 + 89.8 terminal length. | 0.993 | (91, 88) |

| | | | | |
|---|---|---|---|---|
| Sweet cherry (*Prunus avium* L.), | General | $LA = 6.84 – 2.36 \times L + 0.14 \times L^2 – 0.016 \times W \times L^2 + 0.84 \times W \times L$ | 0.981 | (30, 31) |
| Sweet Cherry (*Prunus avium* L.) Tatura - TS) | Van | $LA = 0.678 \times L \times W$ | 0.994 | (21) |
| Sweet Cherry (*Prunus avium* L.), Tatura - TS) | Lapins | $LA = 0.662 \times L \times W$ | 0.994 | (21) |
| Sweet Cherry (*Prunus avium* L.), Tatura - TS) | Bing | $LA = 0.656 \times L \times W$ | 0.994 | (21) |
| Sweet Cherry (*Prunus avium* L.) Vase - TS | Van | $LA = 0.670 \times L \times W$ | 0.994 | (21) |
| Sweet Cherry (*Prunus avium* L.) Vase - TS | Lapins | $LA = 0.654 \times L \times W$ | 0.994 | (21) |
| Sweet Cherry (*Prunus avium* L.) Vase - TS | Bing | $LA = 0.644 \times L \times W$ | 0.994 | (21) |
| Sweet cherry (*Prunus avium* L.) | General | $LA = 6.84 – 2.36 L + 0.14 L2 – 0.016 \times W \times L^2 + 0.84 \times W \times L$ | 0.981 | (34) |
| Sweet cherry (*Prunus avium* L.) | General | $LA = 0.6612 \times L \times W$ | 0.993 | (21) |
| Sweet cherry (*Prunus avium* L.) | Lambert | $LA = – 21.73 + 2.59 \times W + 4.76 \times L – 0.23 \times L^2 + 0.034 \times WL^2 – 0.004 \times L^2$ | 0.996 | (31) |
| Sweet cherry (*Prunus avium* L.) | 0900 Ziraat | $LA = – 21.37 + 2.59 \times W + 4.76 \times L – 0.23 \times L^2 + 0.034 \times W \times L^2 – 0.006 \times L^2$ | 0.996 | (31) |
| Sweet cherry (*Prunus avium* L.) | Van | $LA = – 21.01 + 2.59 \times W + 4.76 \times L – 0.23 \times L^2 + 0.034 \times W\times L^2 – 0.008 \times L^2$ | 0.996 | (31) |
| Sweet cherry (*Prunus avium* L.) | Bing | $LA = – 20.65 + 2.59 \times W + 4.76 \times L – 0.23 \times L^2 + 0.034 \times W \times L^2 – 0.001 \times L$ | 0.996 | (31) |
| Sweet cherry (*Prunus avium* L.) | Stella | $LA = – 19.93 + 2.59 \times W + 4.76 \times L – 0.23 \times L^2 + 0.034 \times W \times L^2 – 0.014 \times L^2$ | 0.996 | (31) |
| Watermelon (*Citrullus lanatus* (Thunb) | General | $LA = 2.99 + 0.50 \times L \times W$ | 0.961 | (81) |
| White mulberry *(Morus alba*) | General | $LA = – 2.12 + 0.68 \times (L \times W)$ | 0.960 | (84) |

LA – leaf area; L – leaf length; W – leaf breadth; N – no. of leaves per seedling; L1, L2, L3 are the length of the apical leafs midrib, the length of the first leaflet nearest to the apical leaf on the left and the length of the first leaflet nearest to the apical leaf on the right, respectively; and W1, W2, W3 are the maximum width of lamina for L1, L2 and L3 respectively; LLCV – length of the leaf central vein; LLL – lower leaflet length; ULL – upper leaf lobe length; X – width of the top of the leaflet; X1 – the width of the side of the leaflet; TS – training system.

**Table 2. Useful leaf area estimation models developed through various studies for vegetable crops**

| **Common/ scientific name** | **Variety** | **Model** | **$R^2$** | **Reference** |
|---|---|---|---|---|
| Amaranth – grain (*Amaranthus cruentus* L.) | General | LA = 1.1132 × Ellipse area + 0.0613 | 0.954 | (49) |
| Basil (*Ocimum basilicum*) | General | $LA = 0.013\ (L^2 \times W^2) + 4.963$ | 0.985 | (6) |
| Brinjal (*Solanum melongela* L.) | Napoli | $LA = 0.4395 \times L \times W^{1.0055}$ or $LA = 0.3379L^2 \times W^{0.6878}$ | 0.937 | (46) |
| Brinjal (*Solanum melongela* L.) | General | LA = 0.641 × L × W | 0.967 | (79) |
| Broccoli (*Brassica oleracea* var. italic) | General | $LA = 3.2834 + 0.0088 \times W^2$ | 0.869 | (67) |
| Broccoli (*Brassica oleracea* var. italic) Hyb. | General | $LA = 3.07 \times W + 1.13 \times W^2$ | 0.970 | (92) |
| Broccoli (*Brassica oleracea* var. italic) Hyb. | BRO 68 | $LA = 1.15\ W^2$ | 0.993 | (92) |
| Broccoli (*Brassica oleracea* var. italic) | General | LA = 1.0674 × Ellipse area - 0.068 | 0.097 | (18) |
| Cabbage (*Brassica oleracea* var. capitata) | General | LA = 5.5981 + 0.8961 × W | - | (67) |
| Cabbage (*Brassica oleracea* var. capitata) | General | LA = 1.1158 × Ellipse area - 0.6975 | 0.985 | (18) |
| Chinese cabbage (*Brassica* rapa subsp pekinensis) | General | LA = 1.1386 × Ellipse area - 0.5421 | 0.953 | (18) |
| Cowpea (*Vigna unguiculata* L) | General | LA = L × W × 0.75 | 0.896 | (93) |
| Cucumber ( *Cucumis sativus* L) | Hokushin | LA = 0.88 × (L × W) – 4.27 | 0.989 | (10) |
| Cucumber ( *Cucumis sativus* L) | Hokushin | LA = 0.859 × (L × W ) + 2.7 | 0.950 | (9) |
| Cucumber (*Cucurbita* spp.) – Hyb. | Excite-Ikki | LA = 0.851 × (L × W ) | 0.990 | (9) |
| Cucumber ( *Cucumis sativus* L) | Calypso | LA = 0.89 × L × W – 20.58 | 0.980 | (80) |
| Faba bean (*Vicia faba* L.) | General | LA = 0.919 + 0.682 × L × W | 0.977 | (70) |
| Green Pepper (*Capsicum annuum* L.) | - | LA = 0.690 × L × W | 0.996 | (28) |
| Green Pepper Pepper (*Capsicum annuum* L.) | General | LA = 0.604 × L × W | 0.980 | (77) |
| Green Pepper Pepper (*Capsicum annuum* L.) | cayenne | LA = 0.615 × L × W | 0.985 | (16) |
| Okra (*Abelmoschus esculentus* L) | General | LA = L × W × 0.62 | 0.999 | (93) |

| | | | | |
|---|---|---|---|---|
| Onion (*Allium cepa*) | Pandero | LA = 0.000199 + 1.277 × L × A25 | 0.925 | (23) |
| Radish (*Raphanus sativus*) | - | LA = 1.636 + 0.193 (L × W) + 0.74 ($W^2$) + 0.975 × L | 0.97 | (83) |
| Red cabbage (*Brassica oleracea* var. capitata f. rubra) | General | LA = - 338.88 + 3.2859 × W | 0.915 | (67) |
| Summer Squash (*Cucurbita pepo*) | General | LA = -8.4 + 0.97 (L × W) | 0.983 | (63) |
| Tomato (*Solanum lycopersicum* L) Hybrid | Facundo | LA = 0.347 (L × W) - 10.7 | 0.980 | (9) |
| Tomato (*Solanum lycopersicum* L) | Jama F1) | LA = 0.5 × L × W | 0.884 | (15) |

LA – leaf area; A25 - Leaf diameter at a distance of 25% of the total leaf length

**Table 3. Useful leaf area estimation models developed through various studies for ornamental crops**

| **Common/ scientific name** | **Variety** | **Model** | **$R^2$** | **Reference** |
|---|---|---|---|---|
| Dahlia (*Dahlia. pinnata*) | General | LA = 0.28 + 0.58 × L × W | 0.994 | (45) |
| Euphorbia (*Euphorbia* × *lomi*) | Thai hybid | LA = 0.691 × L × W – 1.428 | 0.981 | (41) |
| Granium (*Pelargonium* × *hortorum*) | General | LA = 0.07 + 0.68 × L × W L | 0.995 | (45) |
| Gerbera (*Gerbera jamesonii* H. Bolus) | Vital | LA = 0.5 × L × W | 0.909 | (15) |
| Gladiolus (*Gladiolus x gandavensis* and *Gladiolus caryophyllaceus*) | White Friendship and Friendship Pink | LA = 0.62 × L × W | 0.982 | (5) |
| Marigold (*Calendula officinalis* L.) | General | LA = 0.55 + 0.56 × L × W | 0.987 | (45) |
| Roadside woodrose *(Merremia cissoids)* | General | LA = 0.501 × (X) + 2.181 × (Z) | - | (27) |
| Pansy (*Viola wittrockiana*) | General | LA = –0.26 + 0.71 × L × W | 0.992 | (45) |
| Petunia (*Petunia* × *hybrida*) | General | LA = 0.21 + 0.64 × L × W | 0.994 | (45) |
| Phalaenosis plant (*Phalaenosis specis*) – Orchid (Orchidaceae) | NM | LA = 0.6001 + 0.7150 (L × W) | 0.990 | (16) |

| | | | | |
|---|---|---|---|---|
| Rose (*Rosa species*) | General | LA = 0.56 + 0.717 × L × W | 0.991 | (82, 40) |
| Sweet William (*Dianthus barbatus* L.) | General | LA = –0.06 + 0.69 × L × W | 0.992 | (45) |
| Sunflower (*Helianthus annuus* L.) | - | LA = -11.2 × L + 12.3 × W + 0.66 × L × W | 0.94 | (4) |
| Zennia *elegans* (FB) | Liliput | LA = 0.0031 + 0.8003 × L × W | 0.9933 | (71) |
| Zennia *elegans* (FB) | Thumbelina | LA = 0.0021 + 0.8156 × L × W | 0.9925 | (71) |
| Zennia *elegans* (F) | Liliput | LA = 0.001 + 0.8417 × L × W | 0.9932 | (71) |
| Zennia *elegans* (F) | Thumbelina | LA = 0.8318 × L × W | 0.9957 | (71) |
| Zennia *haageana* (FB) | Carpet Persa | LA = 0.0036 + 0.7719 × L × W | 0.986 | (71) |
| Zennia *haageana* (F) | Carpet Persa | LA = 0.0042 + 0.723 × L × W | 0.9638 | (71) |
| *Z. elegans* x *Z. angustifolia* (FB) | Profusion Cherry | LA = 0.0009 + 0.7765 × L × W | 0.9885 | (71) |
| *Z. elegans* x *Z. angustifolia* (F) | Profusion Cherry | LA = 0.0029 + 0.7899 × L × W | 0.9831 | (71) |

LA – leaf area; X – L x W of the principal leaflet; Z – L x W of the primary + secondary leaflets; FB – flower bud stage; F – flowering stage

**Table 4. Useful leaf area estimation models developed through various studies for medicinal crops**

| **Scientific/ local name** | **Model** | **$R^2$** | **Reference** |
|---|---|---|---|
| *Bergenia purpurascens*- winter-red bergenia or purple bergenia | $LA = 1.44 \times W^{1.90}$ | 0.950 | (98) |
| *Calamintha nepeta* - Calamint | $LA = -0.23554 + [1.067838 \times (L \times W)] + [-0.1526 \times (L^2 \times W)]$ | 0.910 | (19) |
| *Coffea Arabica* - Coffee | $LA = 0.6626 (L \times W)^{1.0116}$ | 0.996 | (3) |
| *Laurocerasus officinalis* Roem - Cherry Laurel | $LA = (-55.5877) + (19.98318 \times W) + (-0.83723 \times W^2) + (0.143132 \times L^2)$ | 0.950 | (65) |
| *Combretum leprosum* Mart. - | A = 0.7103 x (L x W) | 0.952 | (14) |

| | | | |
|---|---|---|---|
| bushwillows | | | |
| *Datura stromonium* - Jimson weed | $LA = 19.39368 + (–8.55345 \times L) + (1.5604 \times L^2) + [–0.3006 \times (L^2 \times W)] + [0.3830632 \times (L \times W^2)]$ | 0.960 | (19) |
| *Ecballium elaterium* (L.) A. Rich. - Wild cucumber | $LA = (5.033387) + [0.024014 \times ( L^2 \times W)] + [0.085096 \times (L \times W^2)] + [-0.0049 \times (L^2 \times W^2)$ | - | (66) |
| *Mucuna pruriens* - Horse-eye Bean | $LA = N \times L \times W \times 3 \times 0.74$ or $LA = N \times LAM \times 3 \times 0.96$ | - | (35) |
| *Melissa officinalis*- lemon balm | $LA = 3.233871 + [0.20786 \times (L \times W^2)] + [–0.01064 \times (L^2 \times W^2)]$ | 0.970 | (19) |
| *Mentha piperita* - Peppermint | $LA = 0.102834 + (–0.24204 \times W^2) + [–0.0112 \times (L^2 \times W)] + [0.887465 \times (L \times W)]$ | 0.930 | (19) |
| *Nerium oleander* – oleander (Kaner) | $LA = 6.24034 + [0.153101 \times (L \times W^2)] + [0.034572 \times (L^2 \times W)] + [0.00821 \times (L^2 \times W^2)]$ | 0.980 | (19) |
| *Origanum onites* - mountain mint | $LA = 0.676645 + [0.300381 \times (L^2 \times W)] + [0.044446 \times (L \times W^2)]$ | 0.920 | (19) |
| *Papaver somniferum* - opium poppy | $LA = (114.83) + (-11.355 \times L) + (0.346 \times L^2) + [0.559 \times (L \times W)]$ | - | (66) |
| *Physalis alkekengi* - groundcherry, or winter cherry | $LA = (-5.11148) + 3.868082 \times L^2) + [-0.05963 \times (L^2 \times W)] + [0.008349 \times (L^2 \times W^2)$ | - | (66) |
| *Picrorhiza kurroa* – Picrorhiza or kutka | $LA = 0.333 + 0.603 \times L \times W$ | 0.995 | (52) |
| *Crocus sativus* L - Saffron | $LA = -30.4920 + 0.9163 \times L \times W$ | 0.904 | (51) |
| *Stevia rebaudiana* Bert. - Sugar Leaf | $LA = L \times W \times 0.548$ | 0.960 | (74) |
| *Styrax ferrugineus* - snowbell | $LA = −0.666 + 0.704 \times W \times L$ | 0.972 | (90) |
| *Styrax pohlii* – snowbell | $LA = 0.582 + 0.683 \times W \times L$ | 0.981 | (90) |
| *Leucojum aestivum* L. - Summer Snowflake | $LA = (-5.902) + (-4.12xL) + (0.19 \times L^2) + [-4.8 \times (L \times W^2)] + [0.201 \times (L^2 \times W^2)] + [-0.42 \times (L^2 \times W)] + [10.65 \times (L \times W)$ | 0.970 | (20) |
| *Camelia sinensis* - Tea | $LA = -0.66 + (0.348 \times L) – (0.1555 \times L^2) – (0.133 \times W^2) + [1.084 \times (L \times W)] + [0.0062 \times (L2 \times W)] - [0.033 \times (W^2 \times C)]$ | 0.99 | (97) |
| *Urtica dioica* - common nettle | $LA = –1.1554 + [–0.04145 \times (L^2 \times W)] + [–0.05403 \times (L \times W^2)] + [0.9781 \times (L \times W)] + [0.006555 \times (L^2 \times W^2)]$ | 0.980 | (19) |

| | | | |
|---|---|---|---|
| *Verbascum phlomoids* - Orange Mullein | $LA = (-47.7135) + (9.169684 \times L) + (2.635646 \times W^2) + [0.030192 \times (L^2 \times W)] + [-1.84291 \times (L \times W)$ | | (66) |

LA – leaf area; N - total number of leaves plant$^{-1}$; L, W and LAM are length, width and leaf area meter reading of middle leaflet of 3rd trifoliate leaf from top.