Further Increasing the Capacity of Tea Leaf Withering Troughs

S. K. Das

35, Durganagar Station Road, P.O. Rabindrapally, Kolkata 700065, West Bengal, India
e-mail: skdas202@yahoo.com

ABSTRACT

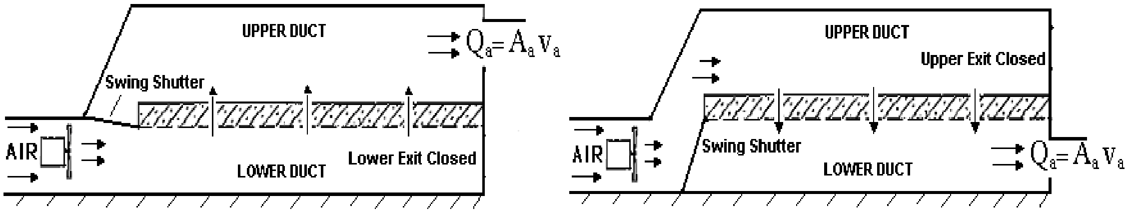
The capacity of tea leaf withering troughs is normally limited up to about 300 mm spread depth and this limitation occasionally becomes critical in the peak season for many tea factories which possess a number of withering troughs of total capacity just enough to properly (uniformly) wither all the tea leaf plucked from the gardens in any normal day. It would certainly be unadvisable to install additional trough(s) only to encounter the occasional inrush of leaf in some days of the peak season. Instead, if the capacity of the withering troughs could be increased either by altering or adjusting some parameters, in addition to those which are already known and being used, not only their better utilization could be ensured, but also the apparent need for installing additional trough unit(s) could be avoided. In such a pursuit two non-conventional parameters viz. ratio between cross-sectional areas of upper and lower ducts, and ratio between durations of alternate upward and downward flow of air through the trough bed were tried, and it was found that particular levels of their adjustments could substantially increase the rate of physical withering (i.e., rate of moisture loss) and thereby increase the withering trough capacity.

Keywords: Tea leaf; withering; trough withering; withering trough; capacity.

1. INTRODUCTION

The first stage of black tea manufacturing is withering, which refers to the changes (physical and chemical) that occur in green tea leaf from the time it is detached from the plant to the time of maceration (Owuor and Orchard, 1989). Physical withering is moisture loss of fresh tea leaf (and related physical changes), while chemical withering involves biochemical changes, which solely depend on time.

Withering of fresh tea leaf is carried out in the tea factories usually in withering troughs (Werkhoven, 1974; Hampton, 1992). Between the two types of withering troughs, the enclosed type has outweighed the earlier developed open type in merits and is most popularly used in different tea countries including India. In an enclosed withering trough, there are two air ducts – one upper and one lower, above and below the leaf-carrying trough bed, respectively. Direct horizontal flow-path of air through either of the ducts is blocked by alternately closing the air-exit of the duct through which the air blast entered, while keeping open the air-exit of the other duct, thereby compelling the air to flow vertically through the perforated trough bed (and the leaf mass spread thereon) before it could pass out of the withering trough. With a view to ensure uniform withering of leaf mass through its different layers, the direction of airflow through the trough bed is reversed at certain time intervals, conventionally each hour, by operating swing dampers and using alternate air-exits of upper and lower ducts. Schematic diagrams of an enclosed withering trough, showing the air flowing through it upward and downward across the trough bed, have been provided in figures 1a and 1b, respectively.



(a) (b)

Figure 1.Schematic diagram of a withering trough, showing (a) upward airflow through trough bed, and (b) downward airflow through the bed
(**Note**: Alternate positions/ conditions of swing damper and air exits may be noticed.)

However, a problem in tea industry often arises for limited capacity of withering troughs, which is up to about 300 mm spread depth. Since a withering trough cannot be used more than once in a day, sufficient capacity must be ensured for the withering troughs in a tea factory to hold and uniformly wither the entire plucked leaf of a day. But in peak seasons, sometimes the total capacity of the withering troughs available in a tea factory falls short of accommodating the whole day's harvest of leaf, when factory management has to overload the withering troughs, spreading leaf in greater depths than the reasonable maximum depth, giving ways to deteriorated withering and degraded final product. With the occasional excessive harvest, sometimes even the need for installing additional trough unit(s) is felt. But it would be neither advisable nor economical to install additional trough(s) only to encounter the occasional inrush of leaf. If the capacity of the existing withering troughs could be increased without increasing their physical dimensions, only by altering or adjusting some variables e.g., aerodynamic parameters, not only their better utilization could be ensured, but also the occasional apparent need for installing additional unit(s) could be avoided. The enhancing effects of some variables, like volume flow rate and velocity of air, and temperature and relative humidity of air, on withering rate are established and well-documented. Therefore, two additional, un-investigated parameters, viz ratio between cross-sectional areas of upper and lower ducts of an enclosed withering trough, and ratio between durations of alternate upward and downward flow of air through the trough bed, were studied with an specially designed and fabricated enclosed withering trough in order to test feasibility of utilization of these two parameters for increasing withering trough capacity.

2. THEORETICAL CONSIDERATIONS

2.1 Expressions for Volume Flow Rate of Air through a Withering Trough

Monitoring and maintenance of such a particular volume flow rate of air Q_a at a specific pressure through the withering trough could be done conveniently at upper air-exit (Fig. 1a) during upward airflow through trough bed and alternately at lower air-exit (Fig. 1b) during downward airflow through trough bed, by means of a pitot tube and a manometer and an adjusted opening area, with the following formulations.

If p_d (N/m^2) is dynamic pressure of air and h (mm) is dynamic pressure head of airflow sensed by a standard pitot tube and indicated on a water-column manometer, the following relations can be written according to fundamental fluid mechanics rules (Yuan, 1988):

$$p_d = (1/2)\rho_a {v_a}^2 \qquad \dots(1)$$

or, $$(h/1000)\rho_w g = (1/2)\rho_a {v_a}^2 \qquad \dots(2)$$

where p_d is dynamic pressure of air, N/m^2; ρ_a is density of air, kg/m^3; v_a is velocity of air, m/s; h is dynamic pressure head of air, mm; ρ_w is density of water, kg/m^3; and g is acceleration due to gravity, m/s^2.

Putting ρ_a = 1.224 kg/m^3, ρ_w = 1000 kg/m^3, and g = 9.81 m/s^2 in equation 2, gives

$$v_a = 4.0037\sqrt{h} \approx 4\sqrt{h} \qquad \dots (3)$$

If h mm water gauge (wg) air pressure (or its equivalent) is maintained at the air-exit of the withering trough having an opening area of A_a (m^2), then volume flow rate of air Q_a in m^3/min (CMM) through the withering trough will be obtained from the formula $Q_a = v_a A_a$; and thus, with necessary transformations for units, it yields

$$Q_a = 240\sqrt{h}A_a \qquad \dots (4)$$

However, the volume flow rate of air through the enclosed withering trough should be

$$Q_a = q_a\, A_b \qquad \dots (5)$$

where Q_a is total volume flow rate of air through the withering trough, CMM; q_a is recommended volume flow rate of air per unit area of trough bed, CMM/m^2 [Between 10.67 and 15.24 CMM per m^2 at 12 mm wg pressure (Gogoi, 1995)]; and A_b is area of trough bed of the withering trough, m^2.

Equation 5 could be used to determine Q_a for a particular withering trough (A_b) and for a particular q_a, and then equation 4 to calculate the necessary air-exit area (A_a).

2.2 Degree of Withering

Percent wither (P_W), which is a measure of degree of withering, may be expressed as

$$P_W = (F_M / I_M) \times 100 \qquad \dots (6)$$

where I_M is initial mass of leaf, kg; F_M is final mass of leaf, kg.

If M_L is moisture loss, in percent (wet basis) of tea leaf during withering, then

$$M_L = (I_M - F_M)/I_M \times 100 \qquad \dots (7)$$

or, $$M_L = 100 - P_W \qquad \dots (8)$$

Thus, percent moisture loss (physical withering) is inversely related to the magnitude of percent wither; the exact relation being the value of percent moisture loss is complement of percent wither, and vice versa.

3. MATERIALS AND METHODS

3.1 Design and Development of an Experimental Withering Trough

Experiments for the withering study were conducted in a specially designed and fabricated enclosed withering trough. A Mechanical Desktop drawing view of the designed withering trough has been provided in figure 2. The experimental withering trough had 1.5 m inner height, and 1 m inner width, and it had a trough bed of size 5 m x 1 m, which could be adjusted at 3 different heights of 400, 500, and 600 mm above the floor (lowest position, middle position, and top position), thereby maintaining 3 different upper and lower duct cross-sectional area ratios, viz 2.75:1, 2:1 and 1.5:1. Its alternate upper and lower air-exit openings were adjustable and a particular volume flow rate of air could be maintained through it at a specific (12 mm wg) pressure by necessary adjustments of rpm of the blower and adjusting the exit area as per calculations of the derived formulas (4) and (5). The ratio between durations of alternate upward and downward airflow through the trough bed could be varied by using different timings of reversal of airflow directions through the bed, using the swing dampers and alternate air-exits. Netlon sheets of any mesh size (35- 45% perforations) could be laid on the welded wire mesh trough bed.

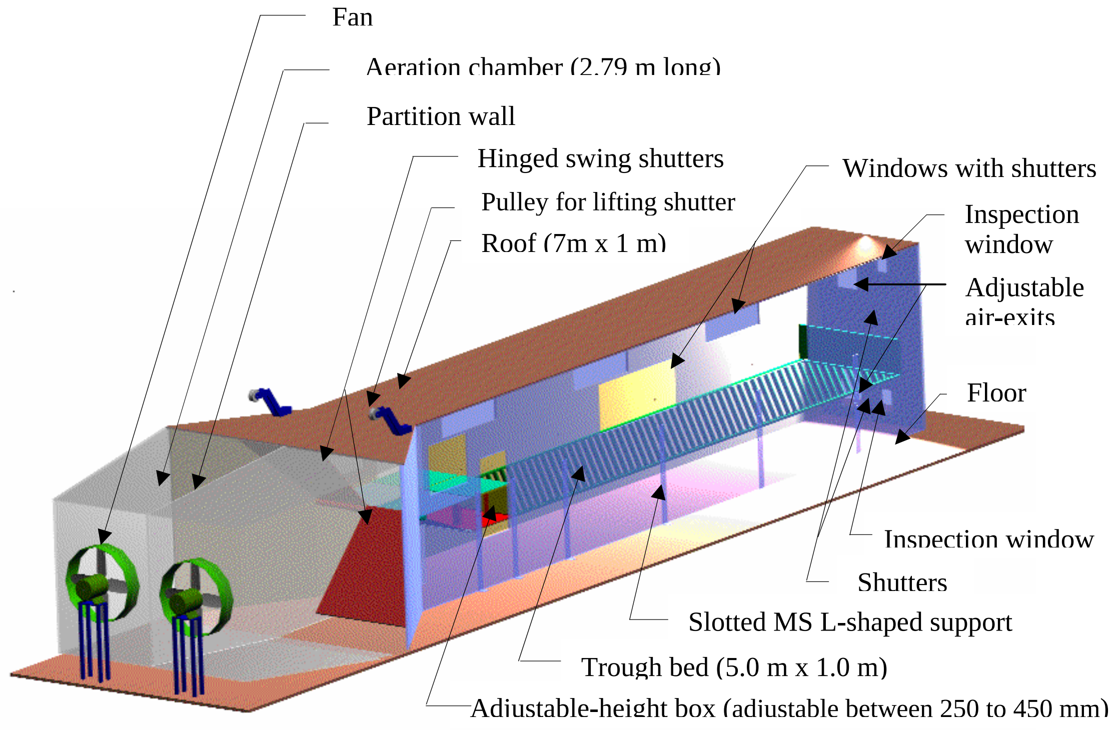


Figure 2. Designed experimental withering trough (shown transparent and semi-transparent in order to illustrate the interiors)
[Length of rectangular tunnel = 7.0 m, Inner height = 1.5 m; width =1.0 m]

3.2 Design of Experiments for Evaluating Effects of Selected Parameters on Withering

Traditionally the trough bed within an enclosed withering trough is fitted horizontally at any level in-between the ceiling and the floor, below the mid-height, usually anywhere at around 1/3rd the height of the withering trough above the floor. But no report on any research for optimizing the bed position, or equivalently, for optimizing the ratio between the cross-sectional areas of upper and lower ducts of an enclosed withering trough, created by the bed's particular position, with regard to maximization of moisture loss or rate of withering, is available. Further, in tea factories, conventionally the reversal of air flow direction through the leaf-carrying trough bed of an enclosed withering trough is made usually at each hour, by raising or lowering the damper flap in front of the fan and operating the alternate air-exits which are equipped with shutters. But, from general perception it is apparent that for uniform withering of leaf mass across the different layers of the leaf bed and for overall greater loss of moisture or greater rate of withering, the lower layers of the thick leaf-bed would require more time-duration of upward-airflow than the duration of downward-airflow through the bed, because the lower layers get more congested, are devoid of natural airflow unlike the upper layers, and surface moisture of the garden-fresh leaves tend to accumulate at the lower layers of the leaf mass.

From the above considerations, the following two withering-related parameters were selected for the present study: (i) ratio between cross-sectional areas of upper and lower ducts (R_x), and (ii) ratio between durations of alternate upward and downward flow of air through the trough bed (R_d). An additional auxiliary parameter viz 'mass of leaf spread per unit area (M_u)' was used with each of the two parameters as an independent variable.

Effects of the selected two variable parameters were evaluated through actual withering experiments at a recommended fixed airflow rate of 10.67 CMM per m^2 of the trough bed at 12 mm wg pressure maintained at the air-exit. The withering experiments were conducted in the months of June through September, over the two years 2001 and 2002. Weather conditions were more or less similar in these months. Temperature and relative humidity of ambient air during the experimental period were within reasonable ranges - 27.2 ˚C to 32.4˚C and 72.1% to 92.0%, respectively; and it was assumed that their variation within these ranges did not significantly affect the effects of the selected parameters on physical withering under experimental conditions. Also, for small variations in the initial moisture contents of tea leaf during this period, effects of variations in the initial moisture contents of tea leaf on the rate of moisture loss or withering was ignored.

Factorial Experiment in Completely Randomized Design (CRD) was used for data analysis and interpretation. The specific designs of the two separate sets of withering experiments are provided below in two subheadings.

3.2.1 For Effect of Ratio between Cross-sectional Areas of Upper and Lower Ducts (R_d)

Dependent variable:

(1) Percent moisture loss of tea leaf during the withering period (10 h).

Independent variables:

The independent variables for the withering experiment, along with their levels and number of replications, are given in Table 1.

Table 1. Independent variables for the experiments to determine effect of ratio between cross-sectional areas of upper and lower ducts (R_x)

No.	Name of the variable	Levels	The selected levels
1	R_x	3	(i) 2.75:1 (lowest position), (ii) 2:1(middle position*), and (iii) 1.5:1 (top position of trough bed)
2	M_u, kg/m^2	4	(i) 15.5, (ii) 19.3, (iii) 23.3, and (iv) 27.0†

* The 'Middle' position was middle of the range of variations of position of the trough bed, which corresponded to 1/3rd the withering trough height. Other two positions were 100 mm apart of it.

† These figures correspond to spread depths of 200, 250, 300 and 350 mm, respectively, for an average bulk density of fresh tea leaf equal to 77.5 kg/m^3 (Werkhoven, 1974).

3.2.2 For Effect of Ratio between Durations of Alternate Upward and Downward Flow of Air through the Trough Bed (R_d)

Dependent variable:

Percent moisture loss of tea leaf during the withering period (10 h).

Independent variables:

Table 2. Independent variables for the experiments to determine the effect of ratio between durations of alternate upward and downward flow of air through trough bed (R_d)

No.	Name of the variable	Levels	The selected levels
1	R_d	2	(i) 1 h: 1h *, and (ii) 2 h: 1h †
2	M_u, kg/m^2	4	(i) 15.5, (ii) 19.3, (iii) 23.3, and (iv) 27.0

Notes: (a) All withering trials for this case were conducted at R_x = 2.75:1.
(b) * Traditionally followed ratio; † A new ratio selected for comparison.

4. RESULTS AND DISCUSSION

4.1 Effect of Ratio between Cross-sectional Areas of Upper and Lower Ducts of the Enclosed Withering Trough (R_x)

It is seen from ANOVA in Table 3 that percent moisture loss for the different values of R_x varied significantly. Percent moisture loss within the withering period of 10 h was the highest for R_x = 2:1, while it was the least for R_x =2.75:1 and moderate for R_x = 1.5:1.

Table 3. ANOVA for effects of ratio between cross-sectional areas of upper and lower ducts (R_x) and leaf mass spread per unit area of trough bed (M_u) on moisture loss

Variable	Levels	Factor means (% moisture loss)	CD (5%)
R_x	2.75:1, 2:1 and 1.5:1	26.75, 30.63, 28.70	1.05
M_u, kg/m^2	15.5, 19.3, 23.3 and 27.0	33.96, 30.96, 25.77, 24.08	1.21

Further, it is seen from ANOVA Table 3 and figure 3 that percent moisture loss decreased significantly for the different values of M_u corresponding to different spread depths. The differences in the moisture losses decreased drastically for the range $15.5 < M_u < 23.3$. Beyond $M_u = 23.3$, up to $M_u = 27.0$, this trend persisted, but the corresponding moisture loss values were tending to differ insignificantly.

The lower layers of leaf mass on the trough bed contains more adhered moisture, therefore for uniform and efficient withering higher upward velocity of air through the trough bed is needed than the downward flow through the trough bed. Therefore, the cross-sectional area of the lower duct should be smaller than the cross-sectional area of the upper duct. For efficient physical withering of the leaf mass on the trough bed the value of R_x should be such that there exits a suitable and compatible balance of pressure and velocity of air in the upper duct and in the lower duct. Such a balance was obtained for R_x = 2:1, so the moisture loss was the maximum at R_x = 2:1.

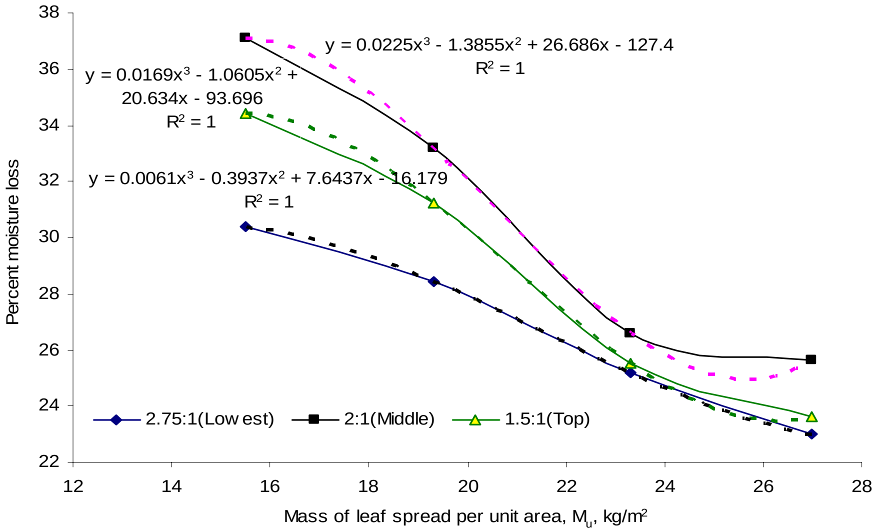


Figure 3. Effect of ratio between cross-sectional areas of upper and lower duct (R_x) and mass of leaf per unit area (M_u) on moisture loss of tea leaf at a ratio between durations of alternate upward and downward airflow through trough bed, R_d = 1 h: 1 h

Note: Legends show values of R_x, followed by corresponding position of bed (in parenthesis)

4.2 Effect of Ratio between Durations of Alternate Upward and Downward Flow of Air through the Trough Bed (R_d)

The results are illustrated and explained with ANOVA in Table 4 and graphs in figure 4.

Table 4. ANOVA for effects of ratio between durations of alternate up- and downward flow of air through trough bed (R_d) and leaf mass spread per unit area (M_u) on moisture loss

Variable	Levels	Factor means (% moisture loss)	CD (5%)
R_d	1 h: 1 h; 2 h: 1 h	26.75, 30.14	1.10
M_u, kg/m^2	15.5, 19.3, 23.3, 27.0	31.99, 30.82, 26.43, 24.54	1.55

It is found from Table 4 and figure 4 that for the trough bed position at the lowest, ie for R_x = 2.75:1, R_d = 2 h: 1 h gave significantly higher percentage moisture loss than the percentage moisture loss caused for the conventionally followed ratio 1 h:1 h (R_d = 1 h:1 h). The percent moisture loss differed non-significantly for M_u between 15.5 and 19.3 kg/m^2, while there was a sharp and significant decrease in it for M_u between 19.3 and 23.3 kg/m^2. Moisture loss was again non-significant for 23.3<M_u <27.0 [kg/m^2].

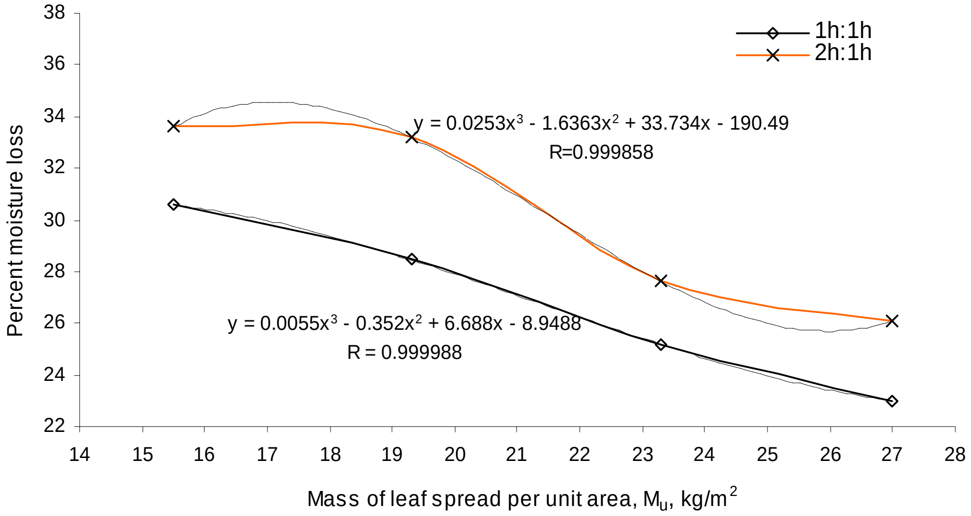


Figure 4. Effect of ratio between durations of alternate upward and downward airflow through trough bed ($R_{d)}$ and mass of leaf per unit area (M_u) on moisture loss of tea leaf at a ratio between cross-sectional areas of upper and lower ducts, R_x = 2.75:1

4.3 Effects of Both Ratio between Cross-sectional Areas of Upper and Lower Ducts (R_x) and Ratio between Durations of Alternate Upward and Downward Airflow through the Trough Bed (R_d)

Effects of both R_x and R_d at different levels (M_u) could be represented by the following multiple regression prediction equation, which have been developed from the data sets of withering trials of the two separate experiments for R_x and R_d.

$$Y = -1487.66+22.02273\, M_u+1484.756\, R_d+158.8022\, R_x -1.11141\, M_u^2 -6.93206\, R_d^2 -71.4156\, R_x^2 + 0.017585\, M_u^3-208.653\, R_d^3+ 10.27109\, R_x^3 \quad (R = 0.98;\ P(\text{error}) = 2.60\%)\ldots\ (9)$$

where Y is percent moisture loss of tea leaf during withering; R_d is ratio between durations of up and downward airflow through trough bed (1 and 2); M_u is mass of leaf spread per unit area, kg/m^2; R_x is ratio between cross-sectional areas of upper and lower ducts (2.75, 2, and 1.5)

This behaviour is also graphically represented in figure 5.

It may be observed from the graphs in figure 5 that the loss of moisture was the lowest for R_x = 2.75 (lowest position of trough bed) with R_d = 2 at M_u ranging between 15.5 and 27.0 kg/m^2. For R_x = 2:1 (middle position of trough bed) with R_d = 2 at M_u = 15.5 kg/m^2 the percent moisture was the maximum. But the withering trough capacity at this value of M_u is very low; only at about 200 mm spread depth.

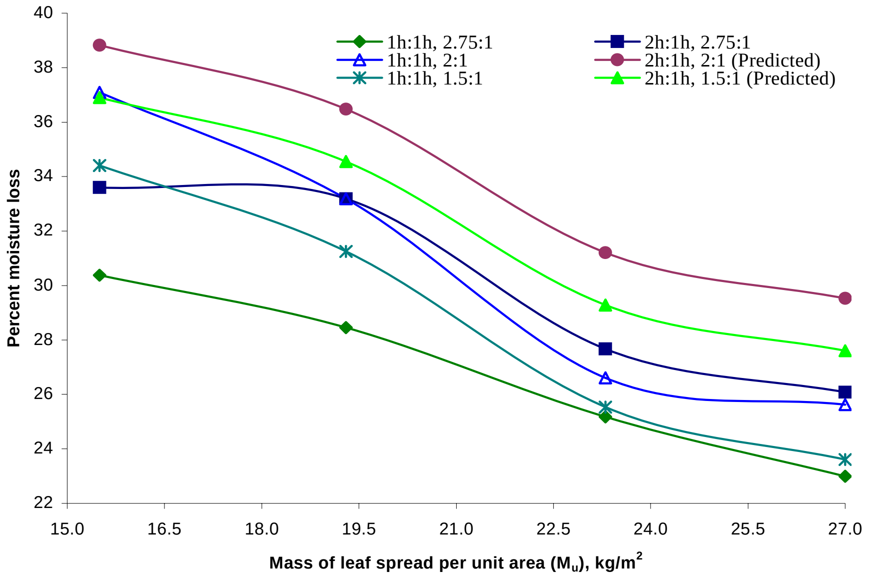


Figure 5. Effects of both R_x and R_d on moisture loss of tea leaf at different values of M_u
[**Note:** pairs of ratios in the legends show values of R_d and R_x, respectively, separated by comma]

At M_u = 19.5 kg/m^2 (250 mm depth), the percent moisture loss for R_x = 2.75 (lowest position) and R_d = 2 for all the cases is higher (or at least at par) compared to that at any value of M_u beyond, say M_u = 20.0 kg/m^2, until M_u = 27.0 kg/m^2. This indicates that as the thickness of leaf increases beyond 250 mm, the moisture loss drops drastically. It implies that although higher values of M_u are to be used to increase withering trough capacity to higher spread depths, but beyond a certain value of M_u the rate of loss of moisture reduces drastically, imposing a limit to which withering trough capacity can be increased.

According to the prediction equation (9), the percent moisture loss from tea leaf for R_x = 2:1 (middle position of trough bed) with R_d = 2 h:1 h at M_u = 27.0 [kg/m^2] would be 29.53 %, which is 15.27 % higher than the moisture loss (25.62%) for R_x = 2:1 (middle position of trough bed) with R_d = 1h:1h at M_u = 27.0, and 13.23% higher than that (26.08 %) for R_x = 2.75:1 (lowest position of trough bed) with R_d = 2 h:1 h at M_u = 27.0.

5. CONCLUSIONS

1. A ratio between cross-sectional areas of upper and lower ducts of an enclosed withering trough at 2:1 (ie R_x = 2:1) gives the maximum moisture loss or the highest rate of physical withering.

2. Similarly, a ratio between alternate upward and downward flow of air through the trough bed at 2: 1 (ie R_d = 2 h: 1h), instead of the conventionally followed 1:1 (R_d = 1 h: 1 h) gives the maximum moisture loss or the highest rate of physical withering.

3. The empirical equation (9) developed with the variables (i) ratio between cross-sectional areas of upper and lower ducts (R_x), (ii) ratio between durations of alternate upward and downward airflow through trough bed (R_d), and (iii) mass of leaf spread per unit area (M_u) could be used to predict moisture loss of tea leaf in the withering trough with a probable error of 2.6%, under the prevailing conditions of the location.

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