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Dedicated

To

Shril Prabhupada

&

My Beloved Parents

ACKNOWLEDGEMENT

All praises to Lord Krishna, whose mercy keeps us alive and enables us to pursue my education in Forestry and Wood Technology Discipline, Khulna University, Khulna and to complete my project thesis for the degree of Bachelor of Science in Forestry (Hones.). Then I would like to express my gratitude to all of my family members specially my parents. Without their continuous inspiration, the present achievement would not be possible.

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ABSTRACT

Allometric equations were developed to describe relationship of mean stem volumes and stand density. The competition-density effect of *Swietenia macrophylla* King in pure stand was analyzed with the reciprocal equation, $w=Kp^{-\alpha}$ where w represent mean stem volume and p represents stand density. The study focused to develop best regression model for measuring the volume of the species and to make relationship between mean stem volumes and stand density. The finding of this study may be potentially used in remote sensing to get result within little time by accounting density,diameter and height. Power equations are found fit for measuring volume. Best regression value for trees 1100-1500 ha^{-1} were found by putting all data separately for DBH (cm), D^2 (cm^2) and D^2H (cm^3) in the graph.Volume is calculated based on sectional diameter and height by using Smalion Frmula. Assuming that, volume is proportional to the D^2H. Mean stem volume is increased with decreasing stand density. The self-thinning line with a slope is -1.22 which is very close -4/3 power law of self-thinning.

Key word: Allometric equations; competition-density; regression model; remote sensing; Power equations; self-thinning.

DECLARATION

I hereby declare that this project thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Khulna University and other institutions.

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APPROVAL

This project thesis has been prepared and submitted to Forestry and Wood Technology Discipline, Khulna University, Khulna, Bangladesh for the partial fulfillment of the requirement of the 4-years professional B.Sc. degree in Forestry and Wood Technology

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LIST OF ABBREVIATIONS

D = Diameter at breast height

D^2H = $(Diameter)^2$ x Height

ha = Hectare

Vol. = Volume

cm = centimeter

m = meter

R^2 = Regression Square

Chapter One

Introduction

1.1 Background and Justification

Swietenia macrophylla is a large deciduous tree with an umbrella-shaped crown frequently reaching heights of over 30 m and diameter at breast height (DBH) of more than 1.5 m. The trunk of *Swietenia macrophylla* is straight, cylindrical, slightly grooved, with well-developed spurs. The crown of young trees is narrow, but in case of old trees they are broad, dense and highly branched. The outer bark of older trees is rough, shaggy, severely longitudinally furrowed and brownish-grey to reddish-brown, and the inner bark is red-brown or pinkish-red. The tree is commercially important timber producing species in Bangladesh.

Allometric relationships are useful in the construction of stocking guides (Seymour and Smith, 1987) and density management (Jack and Long, 1996). At the beginning trees occupy a little amount of light, water, nutrient etc. With the growing larger in stand they require more and more space and gradually the gaps among trees are filled. As the gaps are filled they begin to compete with one another to access resources like light, water, nutrition etc (Silvertown and Charlesworth, 2001). Such interference or competition with the stand induces density-dependent mortality or self-thinning Therefore it is important to know whether allometric relations of stem volume depends on or not.

A stand had reached the maximum or full density; mortality occurred (Yoda et al., 1963) in the following way.

$W= Kp^{-\alpha}$

Where w is the mean phytomass per plant, p is the stand density, K is a constant which varies from species to species and α has been widely reported to take the value of approximately 3/2 for wide range of species (White 1980; Westoby 1984; Zeide 1987). Such a stand is to be following the 3/2 power law of self-thinning (Yoda et al.1963) or it is also called the self-thinning rule. Today most ecologists agree there is no universal value for the slope. From my experiment the slope of self-thinning line is -1.22.

The aim of my study is to develop allometric equations (best regression model) to predict volume from measurement of height and DBH on monoculture of mahogany (*Swietenia macrophylla*) plantations having varying stand density.

1.2 Objectives

- To learn about density and competition effects.
- To know the effects of stand density on volume in *Swietenia macrophylla* King (mahogany).
- To establish allometric relationships of stem volume based on varying stand density in *Swietenia macrophylla* King (mahogany).
- To develop the best regression model for the relationship of density and volume of *Swietenia macrophylla* King (mahogany).

Chapter Two

Literature Review

2.1 General description

The name of mahogany is thought to be derived from a Yoruban word 'M' oganwo', literally meaning a group made up of many object of great height and was introduction to the Caribbean late on(Lamb 1963). The specific name, 'macrophylla', means large leaved. It is derived from Greek words 'makros' means large and 'phyllon' means leaf. Swietenia macrophylla is a large tropical tree, frequently over 30 m in height, DBH commonly 120 to 150 cm but sometimes may be more. S. macrophylla grows well in moist soil. It is generally 30 meters (Zabala, 1990)

Leaves of S. macrophylla are paripinnate, up to 60 cm long; leaflets are ovate, lanceolate, acuminate, slightly oblique, light green or reddish during young stages and dark green and shining during mature stages. Flowers of S. macrophylla are unisexual and trees of the genus are monoecious (Lee and Rao, 1988). The small whitish green coloured flowers are perfect, pentamerous, born in axillaries panicles and a woody capsule resembling a large inverted club (Zabala 1990).

S. macrophylla is one of the most important timbers producing species. The wood is excellent material, interior decoration boat construction, modelsand patterns, woodcarvings, noveltis, toys, musical instruments etc. the recommended uses of mahogany includes moldings,panelling, general joinery works, furniture, weather boards,carvings, small handles, drowing boards, cases, bowl, trays and other similar items.

2.2 Species of *Swietenia*

Swietenia belongs to the family Meliaceae. The genus Swietenia has many species, namely Swietenia macrophylla, S. mahogany, S. humilis, S. fliribanda etc (Zabala, 1978 and Troup, 1921)

2.3 Taxonomic classification

Kingdom:	*Plantae*
Subkingdom:	*Viridaeplantae*
Infrakingdom:	*Streptophyta*
Division:	*Tracheophyta*
Subdivision:	*Spermatophytina*
Infradivision:	*Angiospermae*
Class:	*Magnoliopsida*
Superorder:	*Rosanae*
Order:	*Sapindales*
Family:	*Meliaceae*
Genus:	*Swietenia Jacq.*
Species:	*Swietenia macrophylla King*

2.4 Phenology

Phenology of the tree is likely to be affected by mean daily temperature, rainfall and sunshine (Su et al., 1994) leaf shedding starts in December (Zabala, 1990). It is reported that leaf shedding dry period (Chowdhury, 1940). The species shows some irregularity in leaf shedding. Each tree does not shed leaf each year. Even a single tree does not shed all its leaves from all branches.

Leaf flushing starts in late January- February (Zabala, 1990). There is a possibility that an internal water balance of the tree may regulate the leaf fall (Chowdhury, 1940).

Flowering and fruiting are particularly seasonal. Fruit may be produced from about 15 years old and once a year. Flowers are normally auxiliary panicles. Flowers are small perfect and whitish, greenish in colour (Zabala, 1990). Generally, flowers appear in April-May. Flowering time is varies with locality and season (Su et al., 1994).

2.5 Habitat

2.5.1 Climatic condition

This vegetation formation is limited by the climatic parameters of mean annual temperature of 240C or higher, mean annual precipitation rate between 1000 to 2000 mm and potential evapo-transpiration ratio between 1.00 to 2.00 (Zabala, 1990; Mayhew and Newton, 1998).

S. macrophylla requires a definite rainy season, annual rainfall exceeding 1600 mm and maximum temperature not exceeding 350C (Guiterreez and Martine).

2.5.2 Soil requirement

S. macrophylla is adopted a wide range of soil conditions. This tree has been found growing on the soils of mixed origin, viocanic soil and soil derived from limestone, granite, land site and other sedimentary igneous or metamorphic rock formation (Stevenson 1942).

S. macrophylla is thought to be suited for well-drained upland alluvial plains associated with well-aerated light soil having neutral pH and high organic content (Negros, 1991) avoiding areas subject to prolonged inundation (Bascope et al., 1957).

2.6 Tree morphology

It is a large tropical tree, frequently over 30 meters in height, commonly 120 to 150 cm in diameter but sometimes may be more. It is a soft timber with pinkish to pale brown heart wood with reddish streaks and light pink to yellowish brown sap wood (sing and Bhola, 1980). It produces leaves which are compound, alternate and usually ever pinnate with opposite and alternate leaflets (Zabala, 1990). Bark is grey brown in colour and varies from moderately rough to smooth, in ridges or with large individual scales. Flowers of S. macrophylla are unisexual and trees of genus are monoecious (Lee and Rao, 1988). The small whitish green coloured flowers are perfect, pentamerous and bome in auxiliary panicles (Zabala, 1990).

Numerous small nectarines are found on the petiole, rachis, petiolules and both surfaces of all leaflets of the pinnate compound leaves. They are circular elongated with a smooth secretary surface. Each had an outer zone generally of tree layers of slightly elongated cells with densely staining cytoplasm subtended by two layers of almost clear and rounded cells (Lersten and Rugenstein, 1982).

The fruit is an ovaid 5- valved (occasionally 4- valved) wood capsule, 5 to 15 cm long numerous reddish brown seeds including a terminal oblong wing with a more or less quadrangular body of 1.27 cm wide and 0.64 cm thick seeds are winged only at the upper end (Zabala, 1990).

2.7 Silvicultural characterstics

Light demanding although a little amount of shedding is necessary during seedling stage. It can coppice well but the usual regeneration method is by seed. In general the, the trees those are of age ranging from 1 to 10 years can grow 0.5-1 meter per year in height. On good sites, they grow 1.5 meter per year in height and 1-3 cm per year in DBH. Under intensive management mahogany tree may reach merchantable size of 30 to 50 years of age, depending on site. An annual increment of 53 to 67 cubic meters per hectare appears possible for fully stocked, managed plantation of mahogany on favourable sites under tropical moist forest condition (Zabala, 1990).

2.8 Ecological range

S. macrophylla is found naturally in both tropical dry and tropical wet forest. It can tolerate a wide range of soils and environmental conditions. It has been found on alluvial soils, volcanic soils, heavy clays, lateritic soils and soil derived from limestone, granite and other sedimentary, igneous or metamorphic rock formations within its natural range (Whitmore 1992). *S. macrophylla* is the pioneer species reoccupying degraded agricultural land (Mayhew and Newton 1998), resistant to cyclones and winds (Soerianegara and Lemmens 1993) and they can grow on very poor soils to well-drained soils. The annual rainfall 1000 - 2500 mm with a dry period of 0–4 months is optimum for *S. macrophylla* (Lamb 1966). But it suits 3800 mm annual rainfall in Amazonian Ecuador and Peru (Whitmore 1983). It requires 1000–2000 mm annual precipitation, 24 °C mean annual temperature and1–2 potential evapotranspiration ratio for the optimum natural development f under tropical dry forest conditions (Lamb 1966). In Indonesia, *S. macrophylla* grows at elevations of 0–1500 m above sea level, in areas with a mean annual temperature of 20–28 °C, with the range in the coldest and warmest months being 11–22 °C and 22–30 °C, respectively (Soerianegara and Lemmens 1993).

2.9 Wood characteristics

Swietenia macrophylla is a moderately soft, medium-weight timber. The timber of *S. macrophylla* is valued particularly for its colour, glossy, nicely figured and workability. The colour of heartwood is reddish or pinkish and the sapwood is yellowish. The wood is worked easily with hand tools, has excellent finishing qualities and dimensional stability and attractive appearance (Martawijaya *et al.* 2005). During the manufacture of quality furniture It polishes well and does not crack or bend. The grain of the wood is interlocked, sometimes straight, with a fine to moderately coarse texture (Soerianegara and Lemmens1993).The density of this wood is about 485–850 kg/m3 at 15% moisture content.

2.10 Distribution

2.10.1 Global

Swietenia macrophylla has a wide global distribution, extending from Mexico to Bolivia and central Brazil (Lamb 1966). It grows naturally in Belize, Panama, Bolivia, Brazil, Colombia, Costa Rica, Honduras, Ecuador, Guatemala, Mexico, Nicaragua, Peru and Venezuela. It has been introduced in most tropical countries where it becomes reforestation species especially in the Philippines and India (Troup, 1921), Burma, Bangladesh, the south pacific, Papua New Guinea (Zabala, 1990). It is also found in the Trinidad, Fiji island (Sing et al., 1980 and Cottle, 1959), Indonesia (Soesilitomo, 1992;Siregar et al., 1975 and Abdurrohim, 1996), Puerto Rico (Geary et al., 1973), Costa Rica, Brazil, Australia, Cuba, Portuguese, Maxico (Zabala, 1990), Soloman island(Quintana,1986; Casin and Salita, 1985).

S. macrophylla is widely used for avenue planting in some Asian countries including Indonesia, India and Sri Lanka.

2.10.2 Bangladesh

In 1971, S. macrophylla was first introduced in Calcutta Botanical Garden. In 1889, the species was planted in Kaptai Forest area of Bangladesh. In Bangladesh, it is planted extensively in Chittagong, Cox Bazar and Chittagong Hill Tracts Districts. Besides, it is planted all over the country as roadside tree. It is also planted in farmlands, marginal lands and agroforestry projects.

2.11 Regeneration of mahogany:

Mahogany (Swietenia macrophylla King) is the most commercially important timber species, but it often does not regenerate successfully after harvesting (Negreros-Castillo, 1991; Snook, 1996; Dickinson and Whigham, 1999). To increase mahogany yields by increasing regeneration some effective methods are needed. Mahogany typically regenerates after major disturbances in even aged mixed-species stands (Stevenson, 1927; Oliphant, 1928; Wolffsohn, 1961; Lamb, 1966;Wolffsohn, 1967; Snook, 1993, 1996, 1998, 2000, 2002; Gullison et al., 1996). Slash, fell, fell and leave, and uprooting and pushing away trees using machines are used to regenerate mahogany successfully.

2.12 Control of pests and diseases

The shoot-borer *(Hypsipyla robusta)* is the most destructive pest in *S. macrophylla* plantations. They are mostly attacked on saplings and poles stages when terminal shoots show symptoms of dieback. Older trees are mostly resistance to attack. There is no effective control measure against this pest. Planting of *Acacia mangium* around this plantation may prevent this pest (Matsumoto *et.al.* 1997). Interplanting neem (*Azadirachta indica*) also reduce shoot-borer attacks (Suharti *et al.* 1995).

Extensive pruning until 3 years after planting may reduce the threat of shoot borer.

2.13 Mahogany monoculture

Monoculture or pure mahogany plantation has been established in number of countries. Young plants are usually set out spacing of 2-3 m. In general, planting sites are cleared of woody growth. The results of pure planting are varied and their successes depend largely on local shoot borer populations. In Bangladesh, many pure mahogany plantations have been raised on private basis. The shoot borer attack is not significant and the growth rate seems to be satisfactory. However, the tree farmers usually do not carry out any thinning in stock because of lack in technical aspects.

2.14 Uses of mahogany

Mahogany is one of the most important timber producing trees. Mahoganies are well known in global timber markets and have been traded for centuries. It is used widely in the furniture industry for reproduction furniture, office desks, and cabinetwork. It has also interior use such as rails, shelf-lipping, divisions, cabinet interiors and drawer sides. It is used chiefly for planking, general joinery, keels, hogs, transoms, stems and many other items. In case of various cases it is commonly laminated, e.g. for stems and frames, and used in veneer form in the cold moulding process boat building, where it is suitable for almost all parts of a boat except steamed bent framing. The timber is particularly suitable for use in racing craft where weight is important. It has greater use as a joinery timber for panelling, general interior joinery, mouldings, shells and internal fittings in vans, ambulances and caravans veneers and other purposes where a good quality, medium weight hardwood is required (Farmer, 1972).

The wood is excellent for furniture, interior decoration (doors, paneling, decorative borders), boat construction, models, patterns, wood carvings, novelties, toys, musical instruments etc (Zabala, 1990).

2.15 Allometric relationships of the stem volume

In the previous thesis, mean stem volume showed strong negative relation with stand density where R^2 value was 0.854. In case of mean stem volume and mean height the value was 0.994 that was fitted from curve equation.

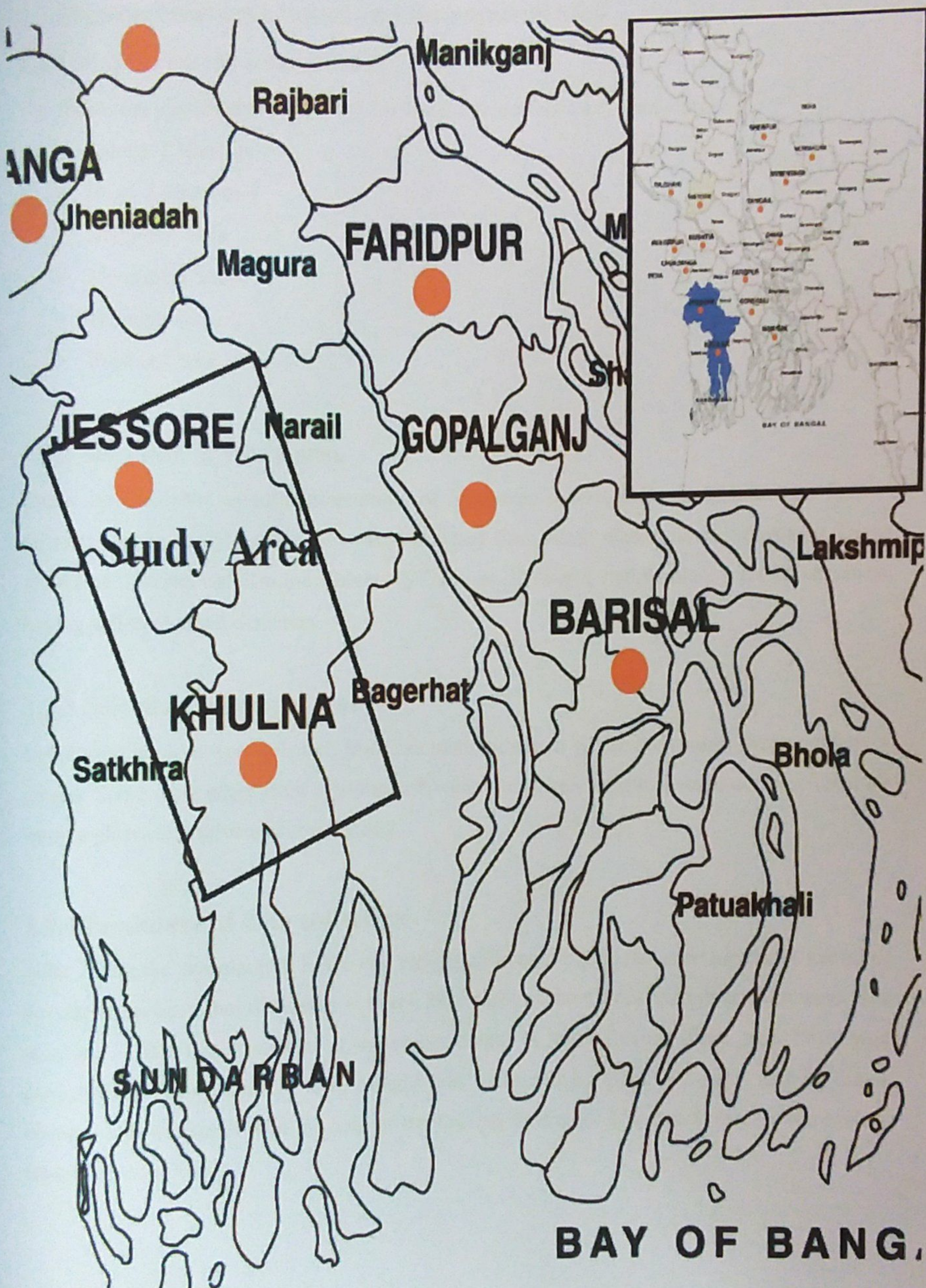
Chapter-Three

Materials and Methods

3.1 Description of the study site

The study was made on pure stands of mahogany (*Swietenia macrophylla* King) at different ages and sizes in Khulna and Jesssore districts in Bangladesh. The latitude of Khulna district is $22^0\ 50^/$ N and longitude is $89^0\ 33^/$ E (Microsoft Encarta, 2007). The area of Khulna is 4394.46 sq. km. and is bounded by Jessore and Narail district on the north, the Bay of Bengal on the south, Bagerhat district on the east and Satkhira district on the west. The average annual temperature is 35.5^0 C and lowest12.5^0C. The annual rainfall of Khulna district is 1710 mm. the main occupation of this district is agriculture. About 36.14% people live on agriculture and 1.66% lives on fishing (Banglapedia, 2007).

The latitude of Jeesore district is $23^0\ 09^/$ N and longitude is $89^0\ 12^/$ E (Microsoft Encarta, 2007). The total area of Jessore is 2578.20 sq. km. of which 23.39 sq.km. is riverine. It is about 26 ft above from the mean sea level. The district is bounded by Jhenaidah district on the north, Magura and Narail districts on the east, Khulna and Satkhira districts on the south and India on the west. The average annual temperature is maximum 31.7^0 C and lowest 20.6^0C and the average relative humidity is about 80 %(BBS, 2000). The annual rainfall of Khulna district is 1710 mm. the main occupation of this district is agriculture. Most of the people live on agriculture.



Source: Banglapedia

Fig.1. Map of the study area

3.2 Measurement techniques and instruments used

3.2.1 Measurement instruments

The following instruments were used for field data collection. These were-

- Spiegel Relaskop
- Hoga Altimeter
- Diameter Tape
- Measuring Tape
- Wooden sticks
- Marker Chalk

3.2.2 Selection of study area

There are available woodlot plantations of *Swietenia macrophylla* in Khulna and Jessore district. For the study sample plots were selected from Ahad plantation at Avaynagar Thana in Jessore districts and Khulna University Campus. Different sample plots were chosen there having different stand densities.

3.2.3 Selection of sample plot

Some sample plots were selected from the plantation area where the canopy was completely closed. Some were taken from medium and some also taken from low stand density. Total 80 sample plots were selected for the study.

3.2.4 Procedure of data collection

After fixing the sample area DBH and Height of every single tree were measured avoiding the edge tree. Sectional diameters at every 2m height of three trees from every plot were also measured. DBH was measured at the breast height (1.3m) of every single tree. DBH was measured by using diameter tape, Height was measured by Haga Altimeter and Sectional diameter was measured with the help of the Spiegel Relaskop. The measurements were taken from the ground.

3.3 Data measurement

3.3.1 Diameter measurement

Diameter was measured at breast height point by using Diameter tape. Diameter of all trees in a plot was measured and recorded. In this way diameter of all plot trees were measured.

3.3.2 Sectional diameter measurement

Sectional diameter was measured by using Spiegel Relaskop. Sectional diameter was measured at every two meter height.

3.3.3 Height measurement

After fixing the sample area, the top and base height of all trees in plot was measured accordingly and recorded. Haga altimeter was used in this measurement. In this way height of all plot trees were measured.

3.4 Data analysis

3.4.1 Allometric equation

The following equations were used to analyse the relationship between volume and density.

i. Linear, $y = a + bx$

ii. *Power*, $y = ax^b$

iii. Exponential, $y = ae^{bx}$

iv. Logarithmic, $y = a + b\ln x$

v. Quadratic, $y = a + bx + cx^2$

vi. Cubic, $y = a + bx + cx^2 + dx^3$

Where y is the dependent variable and x is the independent variable, and *a, b, c, d* is the coefficients.

3.4.2 Sectional diameter calculation

Sectional diameter was calculated by the following formula.

SD=H {L+ 0.25 (S +s)} 2

Where,

H= Distance from the Relaskop to the tree.

L= Large band from the Spiegel Relaskop

S=No of small bands covered.

s=Fraction of the small bands.

3.4.3 Tree volume calculation

From the field data, individual tree volume was calculated by using the following formula

$V = \{\pi L (D_1^2 + D_2^2)\}/8$

Where,

V=Volume of the tree

D_1= Diameter of the 1st part of the section

D_2= Diameter of the 2nd part of the section

L= Length of the section.

3.4.4 Mean tree volume calculation

Mean tree volume was calculated by using the following formula

$$\text{Mean tree volume} = \frac{\sum(V1+V2+V3+\cdots\cdots\cdots+Vn)}{N}$$

Where,

V_1= Volume of 1st tree estimated using allometric equation.

V_2= Volume of 2nd tree estimated using allometric equation.

V_3= Volume of 3rd tree estimated using allometric equation.

....

....

V_n= Volume of n^{th} tree estimated using allometric equation.

N= Total no of tree in a plot

3.4.5 Mean tree diameter calculation

Mean tree diameter was calculated by using the following formula

$$\text{Mean tree DBH} = \frac{\sum(D1+D2+D3+\cdots\cdots+Dn)}{N}$$

Where,

D_1= DBH of 1^{st} tree

D_2= DBH of 2^{nd} tree

D_3= DBH of 3^{rd} tree

D_n=DBH of n^{th} tree

N= Total no of trees in a plot

3.4.6 Mean tree height calculation

Mean tree height was calculated by using the following formula

$$\text{Mean tree volume} = \frac{\sum(H1+H2+H3+\cdots\cdots+Hn)}{N}$$

Where,

H_1= Height of 1^{st} tree

H_2= Height of 2nd tree

H_3= Height of 3rd tree

H_n= Height of n^{th} tree

N= Total no of tree in a plot

3.4.7 Density calculation

Density is the no of tree per unit area. Density in a plot was measured by the following way

$$\text{Density} = \frac{N}{\text{Area}}$$

Where,

N= Total no of tree in a plot

Area of sample plot was $100m^2$

In this study, density was converted per hectare, such as

Density= (N/100) X10000 ha^{-1}

3.5 Self- thinning

Yoda et al., (1963) proposed the relationship between mean stem volume w and stand density p in fully stocked stands during self-thinning processes as,

$W= Kp^{-\alpha}$

Where w is the mean volume per plant, p is the stand density, K is a constant which varies from species to species and α slope of the self-thinning line on w-p diagram, whose value is close to "3/2" or "4/3" according of species, age or site conditions.

In this study I applied MS excel, Kaleida, Sigma plot software for data analysis.

Chapter Four

Results and Discussion

4.1Results

Allometric relationships are useful in the construction of stocking guides (Seymour and Smith, 1987) and density management (Jack and Long, 1996). The competition among individuals increases with the age for light, water, nutrition etc (Silvertown and Charlesworth, 2001). Allometry is important to know the relationship or fitness of the dependent and independent factorc.The relationship between Diameter (cm) at breast height and stem volume (cm^3) at stand density 500-1000 trees ha^{-1} are showed in Fig: 2. which is fitted from the power equation. In the Fig: 3 and Fig: 4 the relationship between D^2 (cm^2) Vs. stem volume (cm^3) and D^2H (cm^3) Vs. stem volume (cm^3) at stand density 500-1000 trees ha^{-1} are respectively showed. In case of 1100-1500 trees ha^{-1} Fig: 5, 6 and 7 are used respectively for Diameter (cm)Vs. stem volume (cm^3), D^2 (cm^2) Vs. stem volume (cm^3) and D^2H (cm^3) Vs. stem volume (cm^3) where all of the best regression lines are fitted from power equation. To fine same relation mentioned above for 1600-2000 trees ha^{-1} Fig: 8, 9 and 10 are used respectively. Fig: 11, 12 and 13 are used 2100-2300 trees ha^{-1}. The relationship between mean stem volume (cm^3) and stand density (ha^{-1}) are given in Fig 14. Mean stem volume showed negative relationship with stand density. Mean stem volume decreased with increasing stand density. Mean stem volume in the high stand density was smaller than in the low density stand. The relationship between mean stem volume and mean tree height is given in Fig 15. It showed positive relationship. Mean stem volume increased with increasing mean tree height. In the Fig 16 the relationship between stand density and stem volume is shown. This showed negative relationship. Mean DBH is higher in low density plot and this decreased with the increased mean stand density.

All of the allomeric data for DBH (cm) and stem volume (cm^3) are fitted in the Fig: 17. It showed that the curve for 1100-1500 trees ha^{-1} is more fitted and the curve for 21-2300 trees ha^{-1} is not fitted. In the Fig: 18 all data of D^2 (cm^2) are applied and it also gave highest value for 1100-1500 trees $ha^{-1}$and not fitted for others. all the data of D^2H (cm^3) are applied in Fig:19 and it also same value like above.

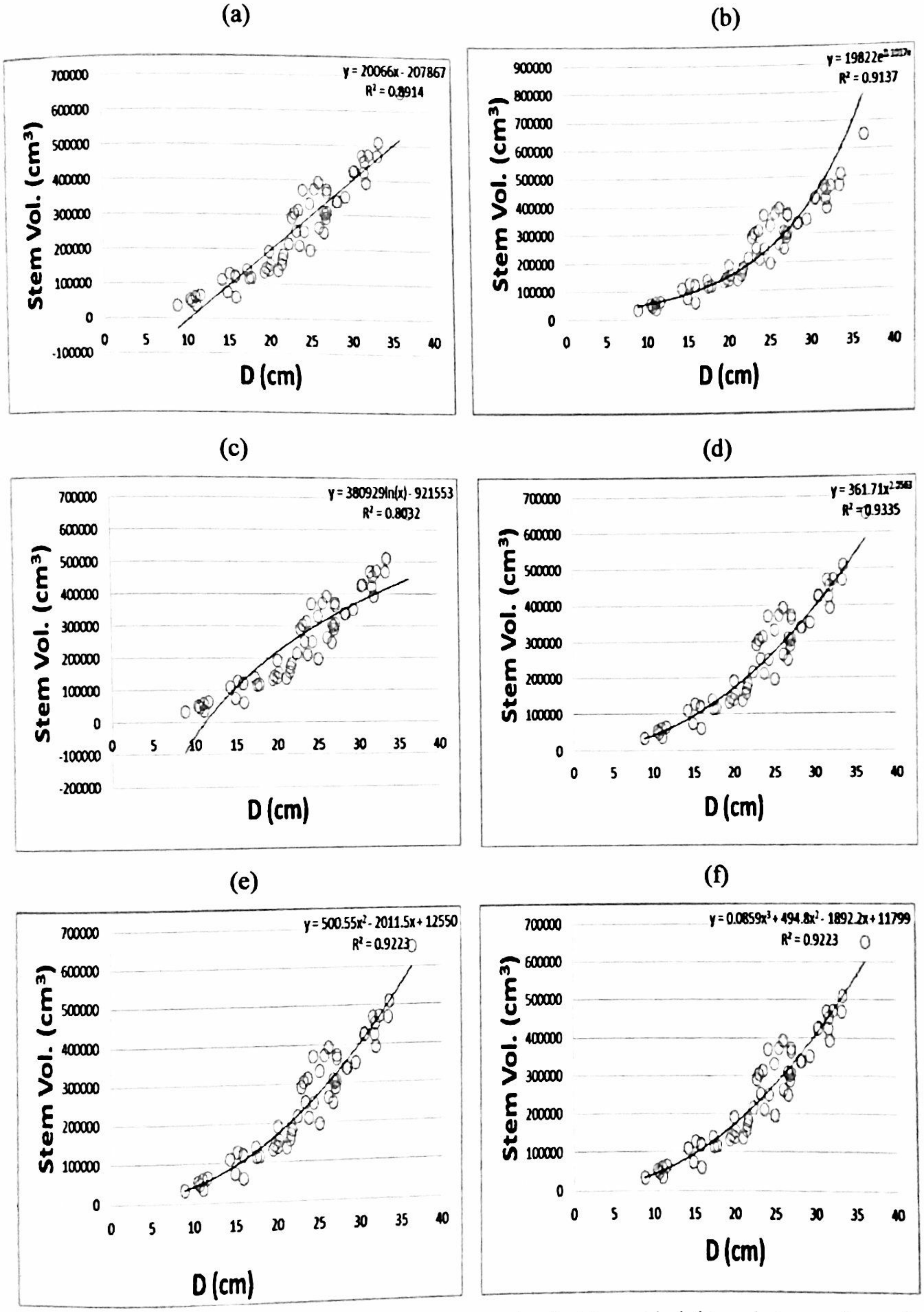


Fig.2. Allometric relationship between Diameter (cm) at breast height and stem volume (cm^3) of *S. macrophylla* at stand density 500-1000 trees ha^{-1}.(a) linear, (b) exponential, (c) logarithmic, (d) power, (e) quadratic, (f) cubic fitting. The best curve fitted from the power equation, here R^2 =0.9335

Table.1.Summary results of different regression model of relationship between DBH (cm) and Volume (cm^3) of *Swietenia macrophylla* at stand density 500-1000 trees ha^{-1}.

Regression Model	Regression Equation	R-square Value
Linear	$y = 20066x - 207867$	$R^2 = 0.8914$
Expon	$y = 19822e^{0.1017x}$	$R^2 = 0.9137$
Log	$y = 380929\ln(x) - 921553$	$R^2 = 0.8032$
Power	$y = 361.71x^{2.0563}$	$R^2 = 0.9335$
Poly 2	$y = 500.55x^2 - 2011.5x + 12550$	$R^2 = 0.9223$
Poly 3	$y = 0.0859x^3 + 494.8x^2 - 1892.2x + 11799$	$R^2 = 0.9223$

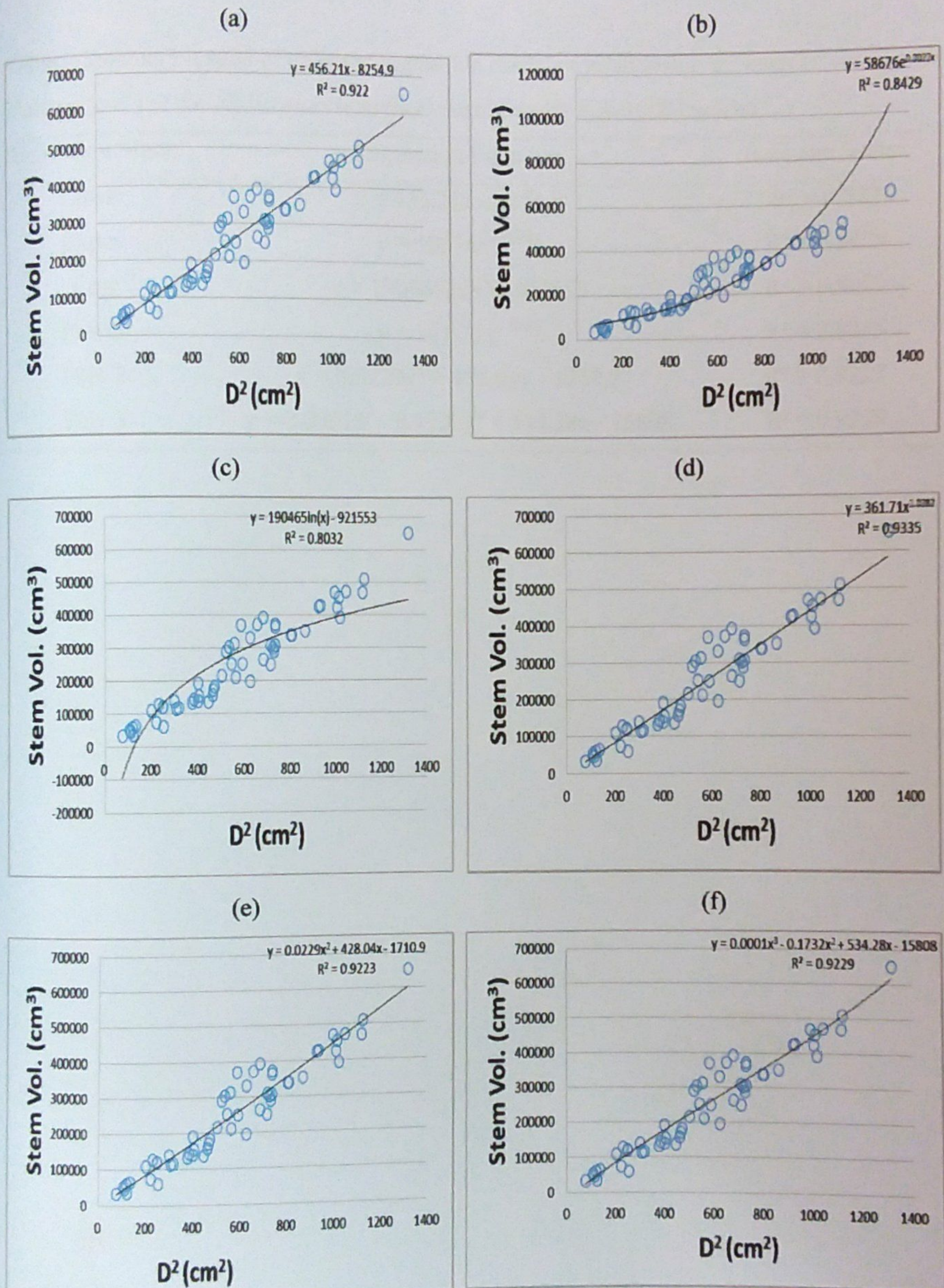


Fig.3. Allometric relationship between D^2 (cm^2) at breast height and stem volume (cm^3) of *S. macrophylla* at stand density 500-1000 trees ha^{-1}. (a) linear, (b) exponential, (c) logarithmic, (d) power, (e) quadratic, (f) cubic fitting. The best curve fitted from the power equation, here R^2=0.9335

Table.2.Summary results of different regression model of relationship between D^2 (cm^2) and Volume (cm^3) of *Swietenia macrophylla* at stand density 500-1000 trees ha^{-1}.

Regression Model	Regression Equation	R-square Value
Linear	$y = 456.21x - 8254.9$	$R^2 = 0.922$
Expon	$y = 58676e^{0.0022x}$	$R^2 = 0.8429$
Log	$y = 190465\ln(x) - 921553$	$R^2 = 0.8032$
Power	$y = 361.71x^{1.0282}$	$R^2 = 0.9335$
Poly 2	$y = 0.0229x^2 + 428.04x - 1710.9$	$R^2 = 0.9223$
Poly 3	$y = 0.0001x^3 - 0.1732x^2 + 534.28x - 15808$	$R^2 = 0.9229$

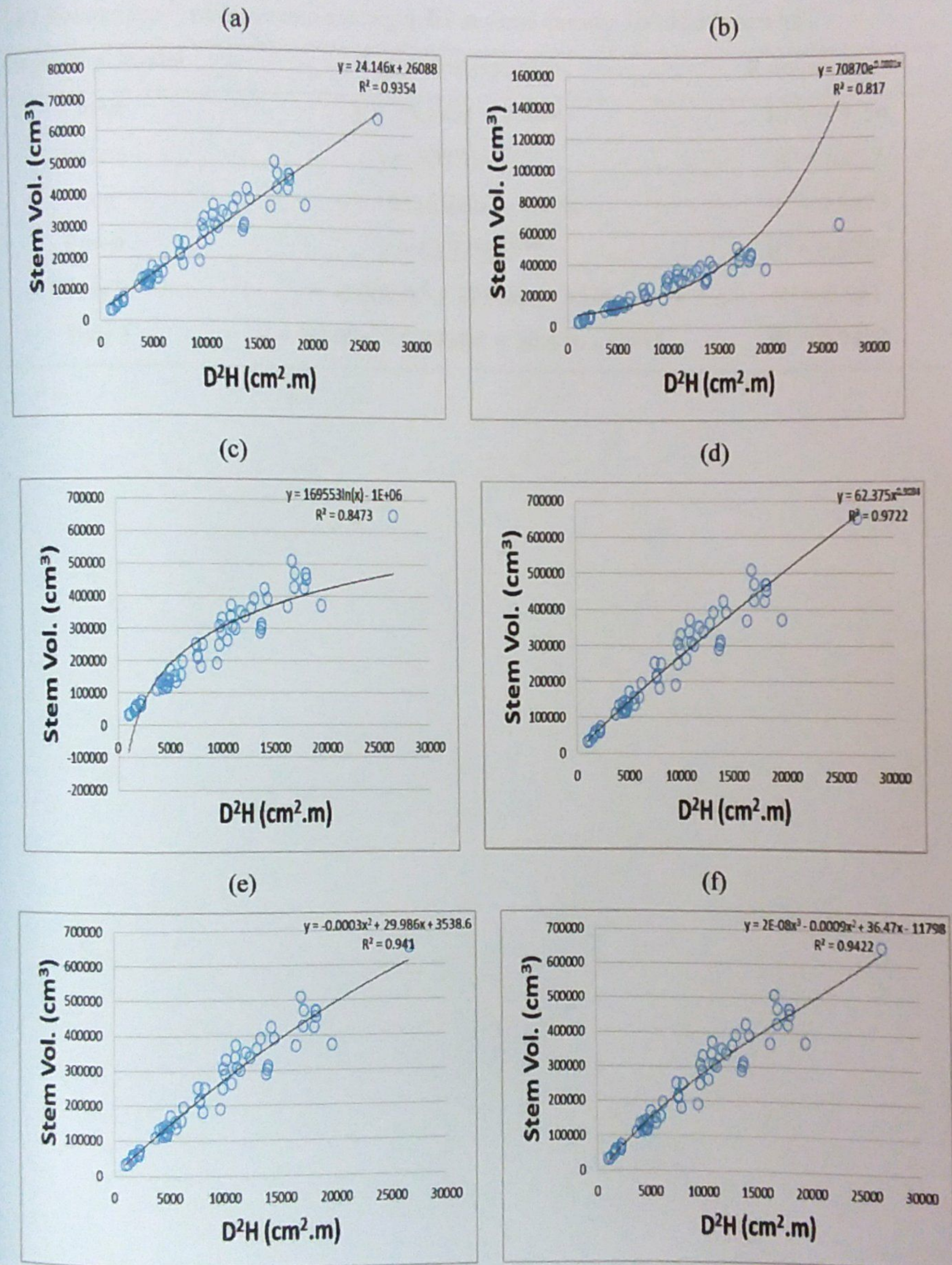


Fig.4. Allometric relationship between D^2H ($cm^2.cm$) and stem volume (cm^3) of *S. macrophylla* at stand density 500-1000 trees ha^{-1}. (a) linear, (b) exponential, (c) logarithmic, (d) power, (e) quadratic, (f)cubic fitting. The best curve fitted from the power equation, here R^2=0.9722

Table.3.Summary results of different regression model of relationship between D^2H ($cm^2.cm$) and Volume (cm^3) of *Swietenia macrophylla* at stand density 500-1000 trees ha^{-1}.

Regression Model	Regression Equation	R-square Value
Linear	$y = 24.146x + 26088$	$R^2 = 0.9354$
Expon	$y = 70870e^{0.0001x}$	$R^2 = 0.817$
Log	$y = 169553\ln(x) - 1E+06$	$R^2 = 0.8473$
Power	$y = 62.375x^{0.9094}$	$R^2 = 0.9722$
Poly 2	$y = -0.0003x^2 + 29.986x + 3538.6$	$R^2 = 0.941$
Poly 3	$y = 2E\text{-}08x^3 - 0.0009x^2 + 36.47x - 11798$	$R^2 = 0.9422$

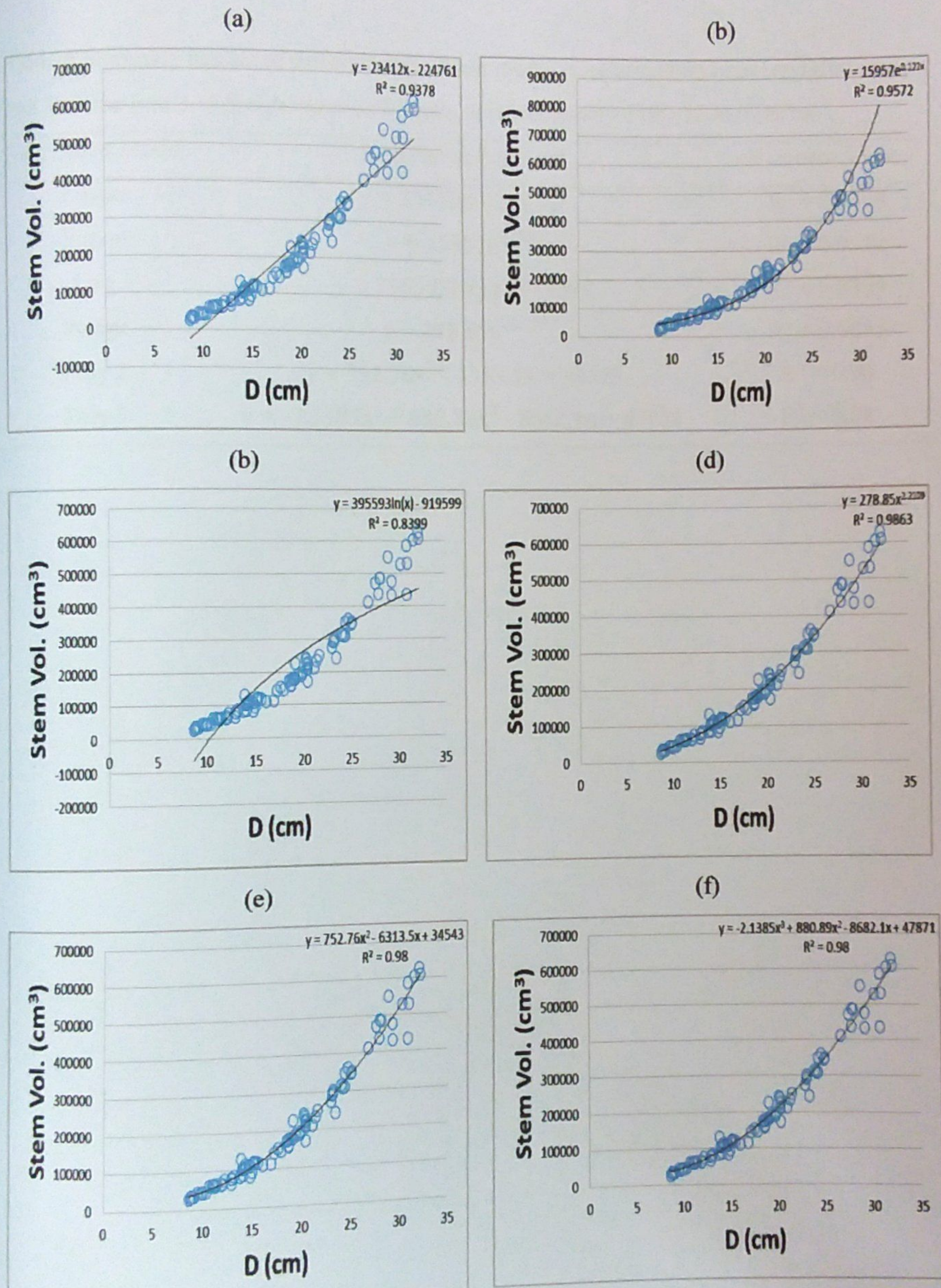


Fig.5. Allometric relationship between DBH(cm) and stem volume of *S. macrophylla* at stand density 1100-1500 trees ha^{-1}.(a) linear, (b) exponential, (c) logarithmic, (d) power, (e) quadratic, (f)cubic fitting. The best curve fitted from the power equation, here R^2=0.9863

Table.4.Summary results of different regression model of relationship between DBH (cm) and Volume (cm^3) of *Swietenia macrophylla* at stand density 1100-1500 trees ha^{-1}.

Regression Model	Regression Equation	R-square Value
Linear	$y = 23412x - 224761$	$R^2 = 0.9378$
Expon	$y = 15957e^{0.122x}$	$R^2 = 0.9572$
Log	$y = 395593\ln(x) - 919599$	$R^2 = 0.8399$
Power	$y = 278.85x^{2.2109}$	$R^2 = 0.9863$
Poly 2	$y = 752.76x^2 - 6313.5x + 34543$	$R^2 = 0.98$
Poly 3	$y = -2.1385x^3 + 880.89x^2 - 8682.1x + 47871$	$R^2 = 0.98$

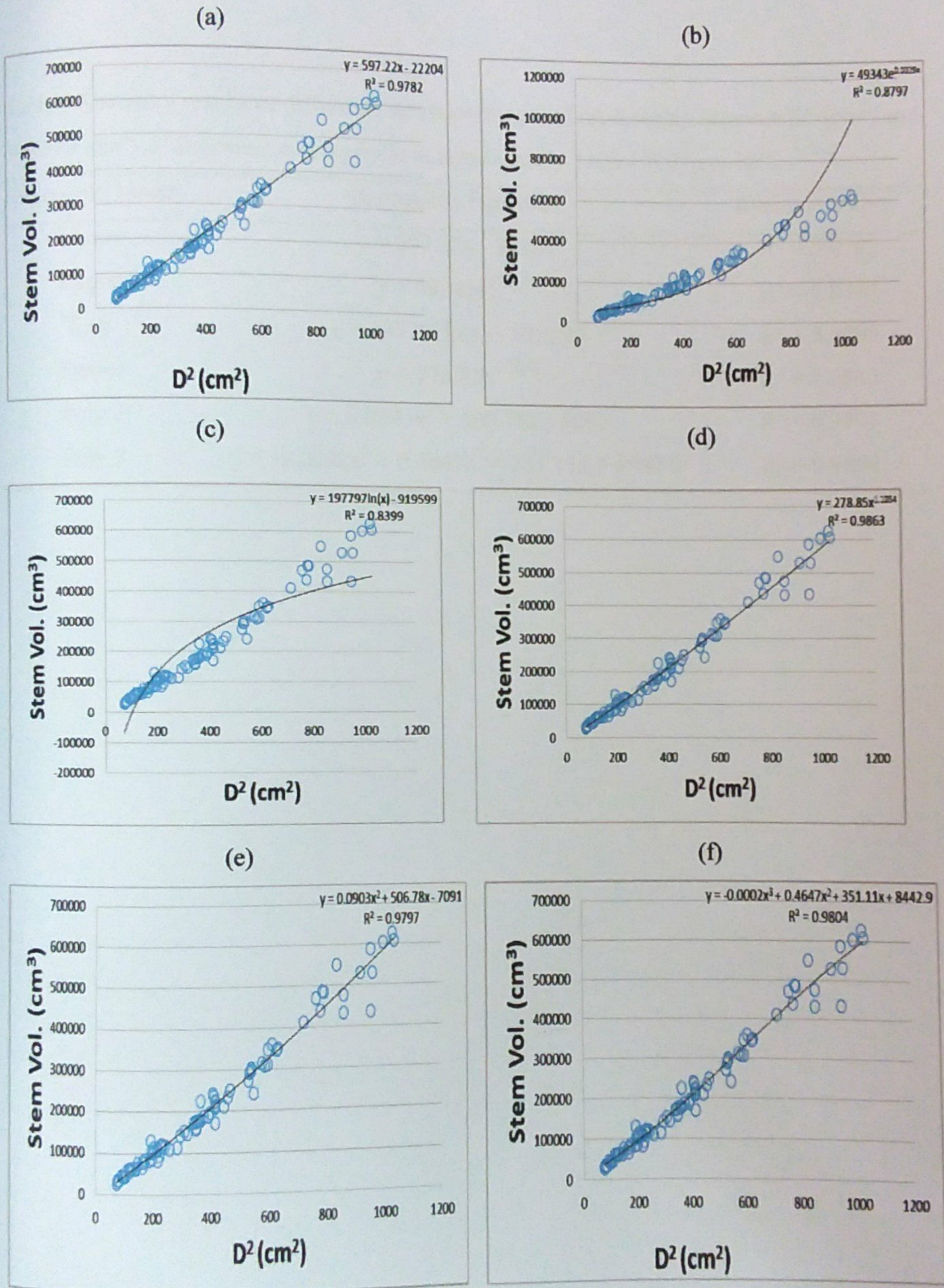


Fig.6. Allometric relationship between D^2 (cm^2) at breast height and stem volume (cm^3) of *S. macrophylla* at stand density 1100-1500 trees ha^{-1}. (a) linear, (b) exponential, (c) logarithmic, (d) power, (e) quadratic, (f)cubic fitting. The best curve fitted from the power equation, here R^2=0.9863

Table.5.Summary results of different regression model of relationship between D^2 (cm^2) and Volume (cm^3) of *Swietenia macrophylla* at stand density 1100-1500 trees ha^{-1}.

Regression Model	Regression Equation	R-square Value
Linear	$y = 597.22x - 22204$	$R^2 = 0.9782$
Expon	$y = 49343e^{0.0029x}$	$R^2 = 0.8797$
Log	$y = 197797\ln(x) - 919599$	$R^2 = 0.8399$
Power	$y = 278.85x^{1.1054}$	$R^2 = 0.9863$
Poly 2	$y = 0.0903x^2 + 506.78x - 7091$	$R^2 = 0.9797$
Poly 3	$y = -0.0002x^3 + 0.4647x^2 + 351.11x + 8442.9$	$R^2 = 0.9804$

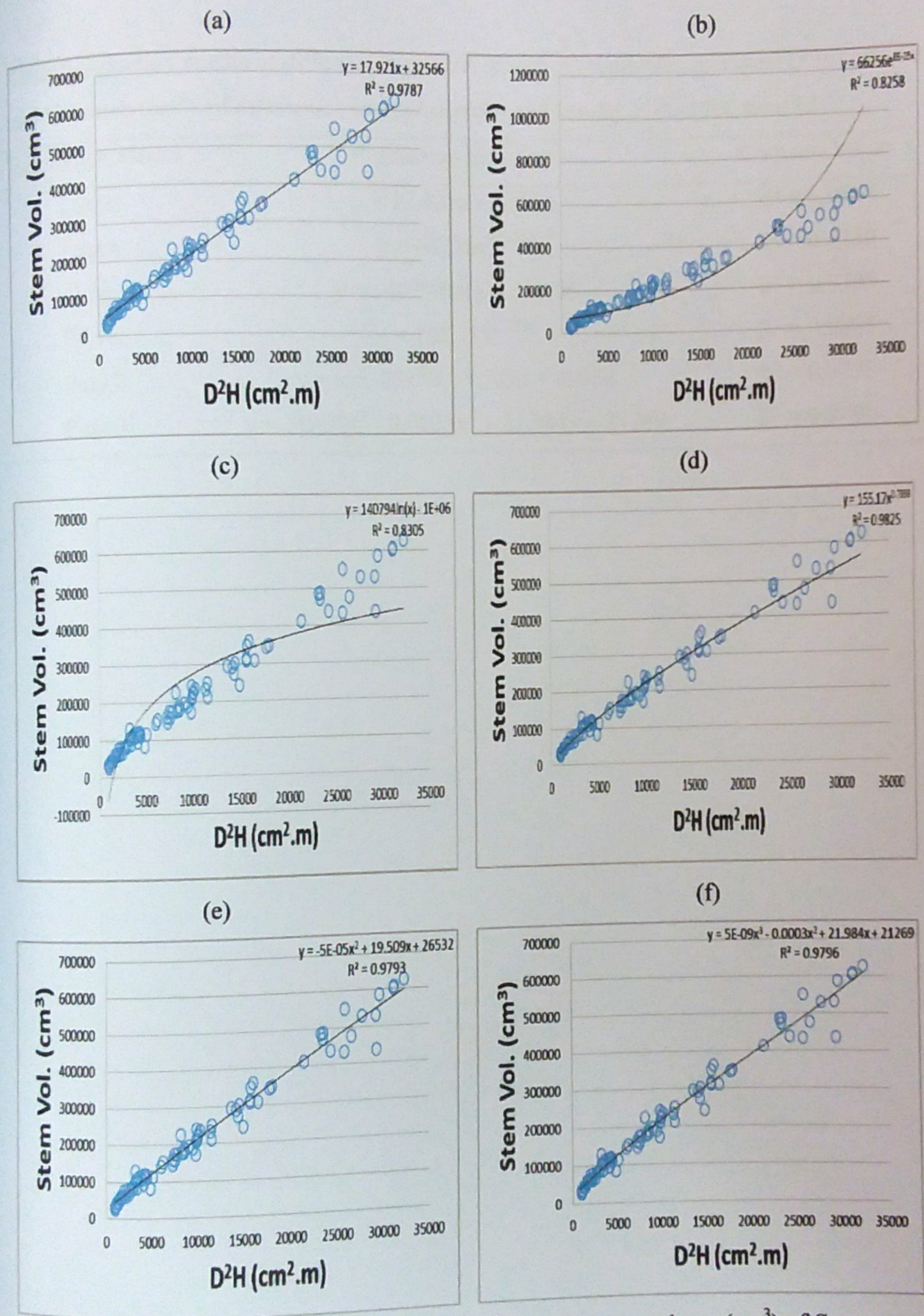


Fig.7. Allometric relationship between D^2H ($cm^2.cm$) and stem volume (cm^3) of *S. macrophylla* at stand density 1100-1500 trees ha^{-1}. (a) linear, (b) exponential, (c) logarithmic, (d) power, (e) quadratic, (f) cubic fitting. The best curve fitted from the power equation, here R^2=0.9825

Table.6.Summary results of different regression model of relationship between D^2H ($cm^2.cm$) and Volumeb (cm^3) of *Swietenia macrophylla* at stand density 1100-1500 trees ha^{-1}.

Regression Model	Regression Equation	R-square Value
Linear	$y = 17.921x + 32566$	$R^2 = 0.9787$
Expon	$y = 66256e^{8E-05x}$	$R^2 = 0.8258$
Log	$y = 140794\ln(x) - 1E+06$	$R^2 = 0.8305$
Power	$y = 155.17x^{0.7898}$	$R^2 = 0.9825$
Poly 2	$y = -5E-05x^2 + 19.509x + 26532$	$R^2 = 0.9793$
Poly 3	$y = 5E-09x^3 - 0.0003x^2 + 21.984x + 21269$	$R^2 = 0.9796$

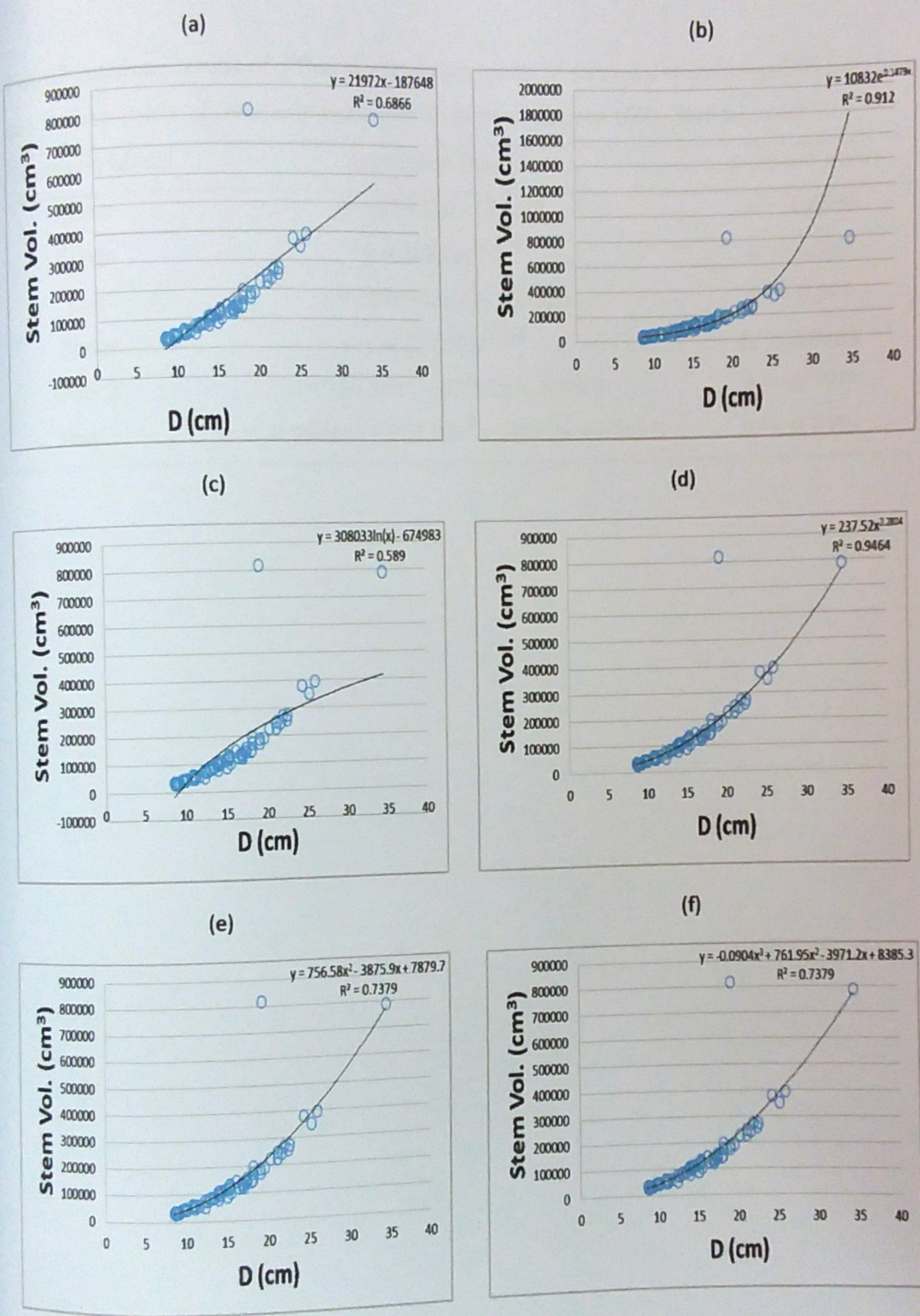


Fig. 8. Allometric relationship between Diameter (cm) at breast height and stem volume (cm^3) of *S. macrophylla* at stand density 1600-2000 trees ha^{-1}. (a) linear, (b) exponential, (c) logarithmic, (d) power, (e) quadratic, (f)cubic fitting. The best curve fitted from the power equation, here R^2=0. 0.9464

Table:7 Summary results of different regression model of relationship between DBH(cm) and Volume (cm^3) of *Swietenia macrophylla* at stand density 1600-2000 trees ha^{-1}.

Regression Model	Regression Equation	R-square Value
Linear	$y = 21972x - 187648$	$R^2 = 0.6866$
Expon	$y = 10832e^{0.1479x}$	$R^2 = 0.912$
Log	$y = 308033\ln(x) - 674983$	$R^2 = 0.589$
Power	$y = 237.52x^{2.2804}$	$R^2 = 0.9464$
Poly 2	$y = 756.58x^2 - 3875.9x + 7879.7$	$R^2 = 0.7379$
Poly 3	$y = -0.0904x^3 + 761.95x^2 - 3971.2x + 8385.3$	$R^2 = 0.7379$

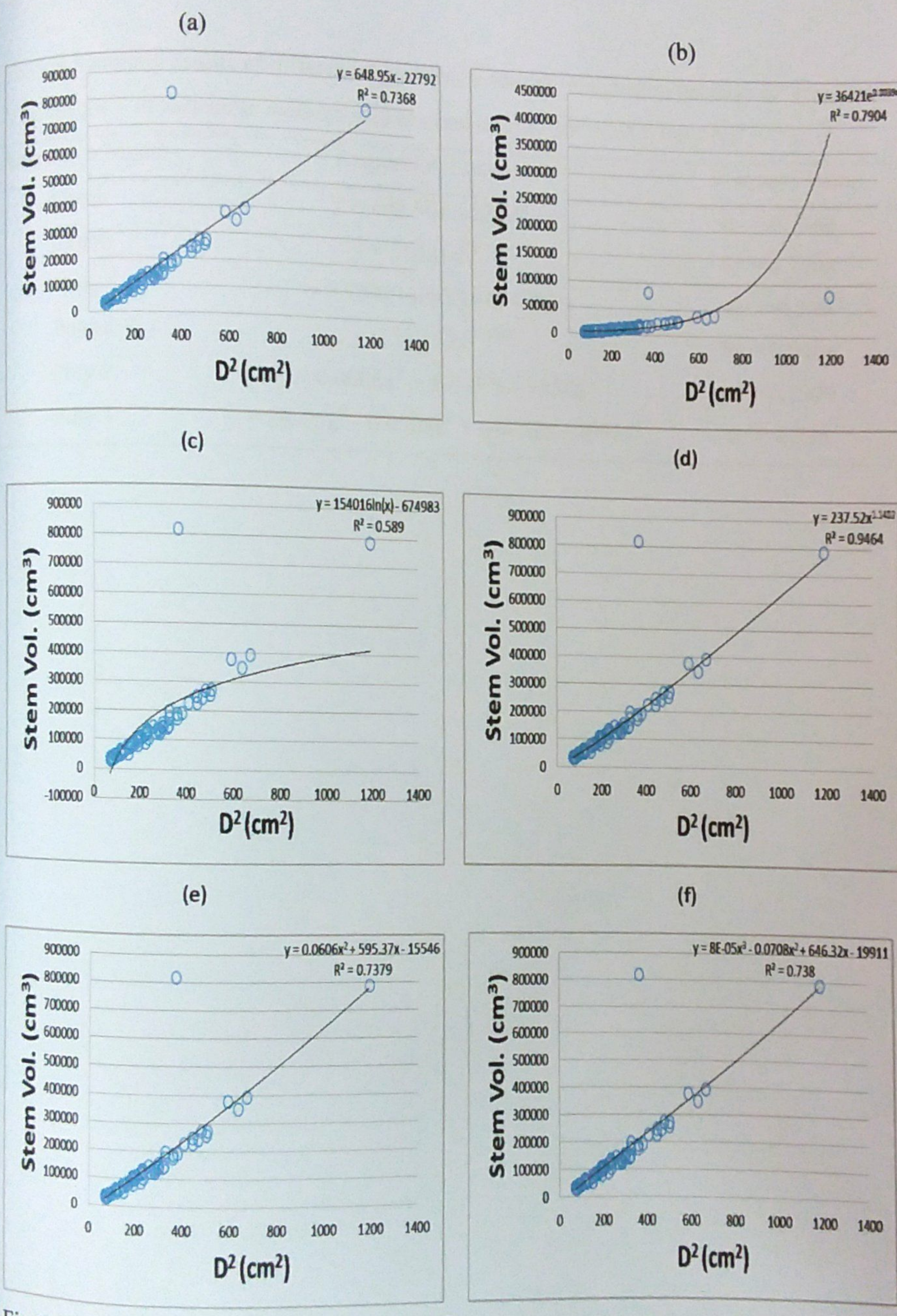


Fig:9 Allometric relationship between D^2 (cm^2) at breast height and stem volume (cm^3) of *S. macrophylla* at stand density 1600-2000 trees ha^{-1}. (a) linear, (b) exponential, (c) logarithmic, (d) power, (e) quadratic, (f) cubic fitting. The best curve fitted from the power equation, here $R^2 = 0.9464$.

Table:8 Summary results of different regression model of relationship between D^2 (cm^2) and Volume(cm^3) of *Swietenia macrophylla* at stand density 1600-2000 trees ha^{-1}.

Regression Model	Regression Equation	R-square Value
Linear	$y = 648.95x - 22792$	$R^2 = 0.7368$
Expon	$y = 36421e^{0.0039x}$	$R^2 = 0.7904$
Log	$y = 154016\ln(x) - 674983$	$R^2 = 0.589$
Power	$y = 237.52x^{1.1402}$	$R^2 = 0.9464$
Poly 2	$y = 0.0606x^2 + 595.37x - 15546$	$R^2 = 0.7379$
Poly 3	$y = 8E\text{-}05x^3 - 0.0708x^2 + 646.32x - 19911$	$R^2 = 0.738$

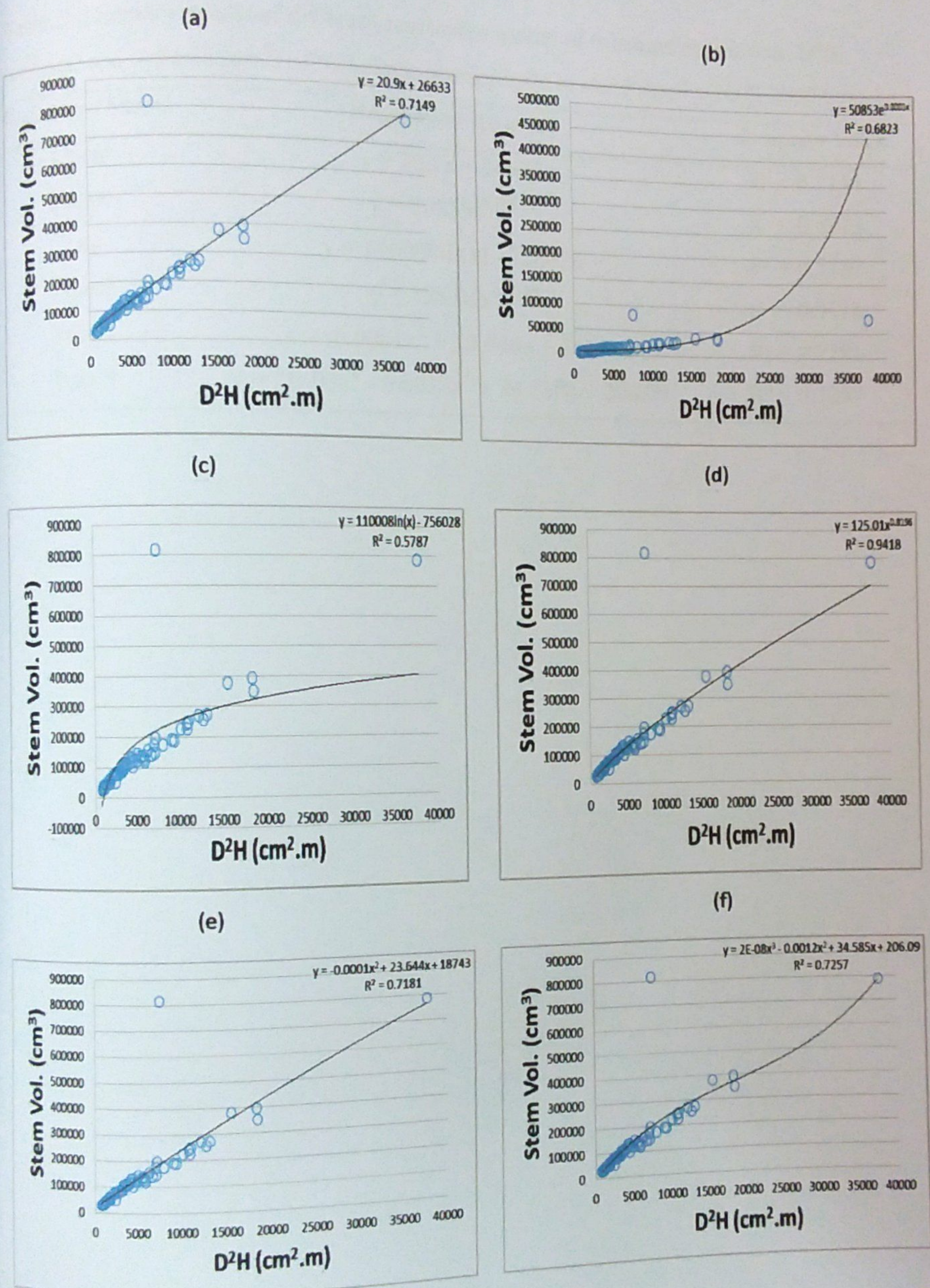


Fig:10 Allometric relationship between D^2H (cm^2.cm) and stem volume (cm^3) of *S. macrophylla* at stand density 1600-2000 trees ha^{-1}. (a) linear, (b) exponential, (c) logarithmic, (d) power, (e) quadratic, (f)cubic fitting. The best curve fitted from the power equation, here $R^2 = 0.9418$.

Table: 9 Summary results of different regression model of relationship between D^2H ($cm^2.cm$) and Volume (cm^3) of *Swietenia macrophylla* at stand density 1600-2000 trees ha^{-1}.

Regression Model	Regression Equation	R-square Value
Linear	$y = 20.9x + 26633$	$R^2 = 0.7149$
Expon	$y = 50853e^{0.0001x}$	$R^2 = 0.6823$
Log	$y = 110008\ln(x) - 756028$	$R^2 = 0.5787$
Power	$y = 125.01x^{0.8196}$	$R^2 = 0.9418$
Poly 2	$y = -0.0001x^2 + 23.644x + 18743$	$R^2 = 0.7181$
Poly 3	$y = 2E\text{-}08x^3 - 0.0012x^2 + 34.585x + 206.09$	$R^2 = 0.7257$

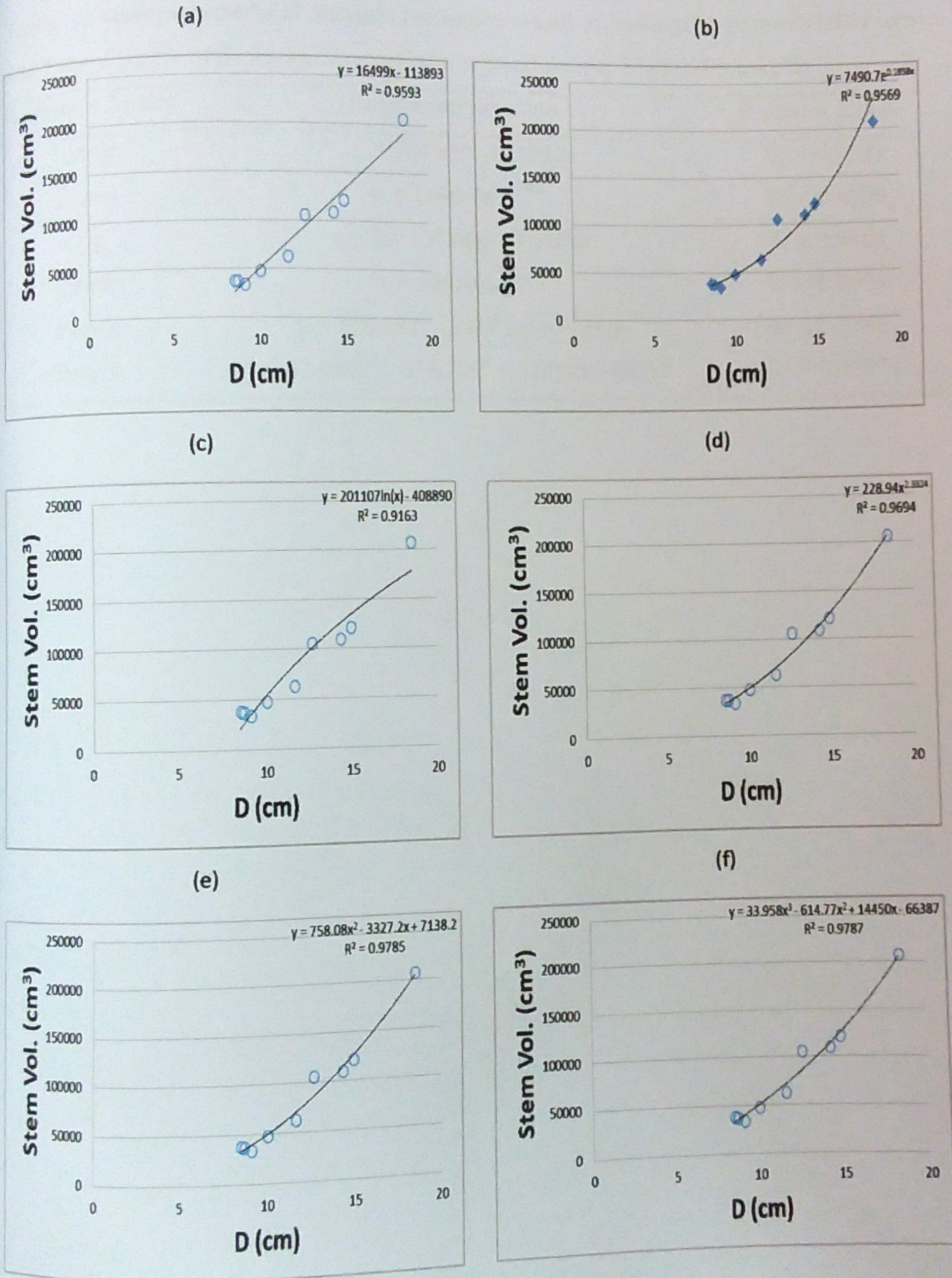


Fig: 11 Allometric relationships between Diameter (cm) at breast height and stem volume (cm^3) of *S. macrophylla* at stand density 2100-2300 trees ha^{-1}. (a) Linear, (b) exponential, (c) logarithmic, (d) power, (e) quadratic, (f) cubic fitting. The best curve fitted from the cubic equation, here $R^2 = 0.9787$.

Tablle: 10 Summary results of different regression model of relationship between DBH (cm) and Volume (cm^3) of *Swietenia macrophylla* at stand density 2100-2300 trees ha^{-1}.

Regression Model	Regression Equation	R-square Value
Linear	$y = 16499x - 113893$	$R^2 = 0.9593$
Expon	$y = 7490.7e^{0.1858x}$	$R^2 = 0.9569$
Log	$y = 201107\ln(x) - 408890$	$R^2 = 0.9163$
Power	$y = 228.94x^{2.3324}$	$R^2 = 0.9694$
Poly 2	$y = 758.08x^2 - 3327.2x + 7138.2$	$R^2 = 0.9785$
Poly 3	$y = 33.958x^3 - 614.77x^2 + 14450x - 66387$	$R^2 = 0.9787$

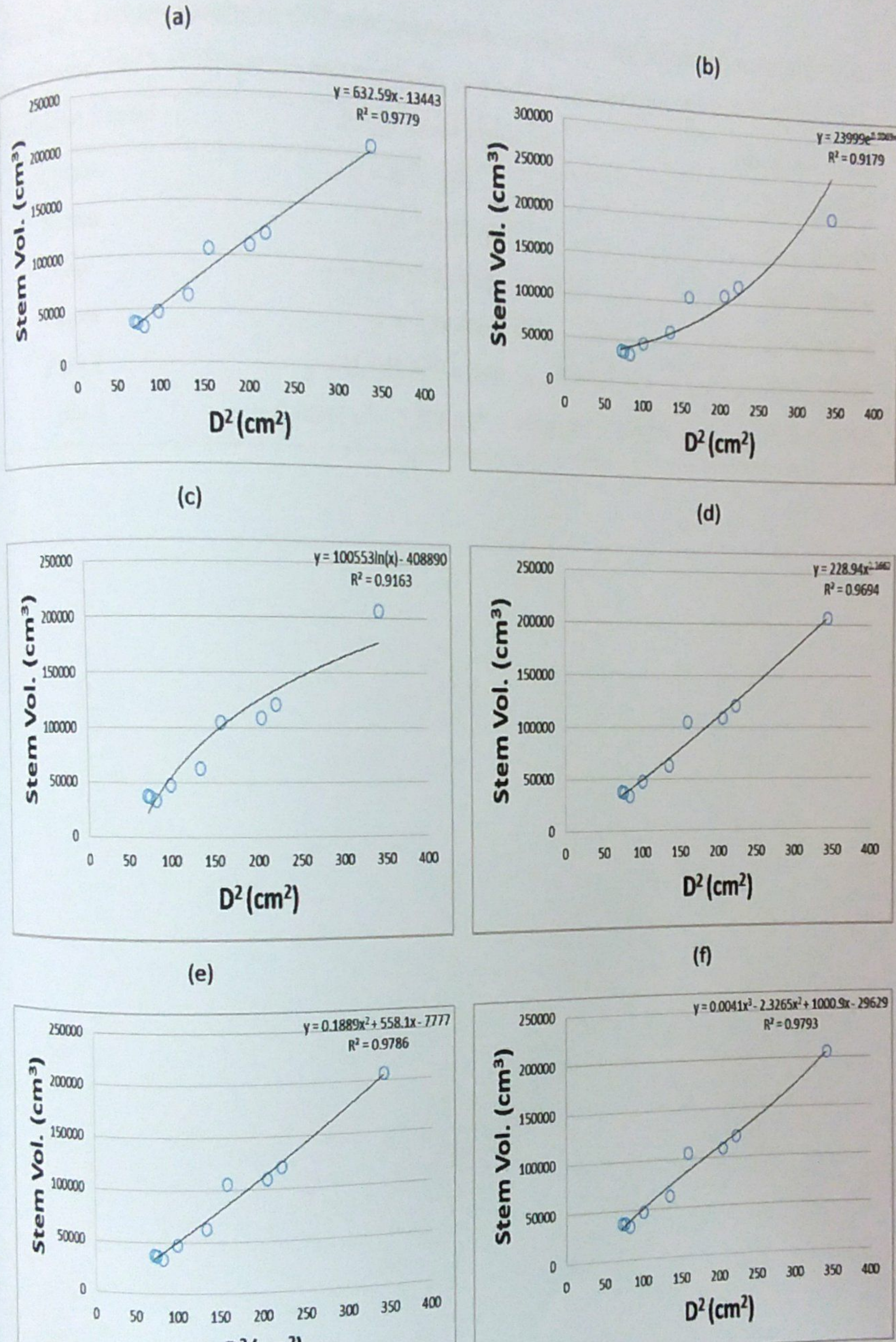


Fig: 12 Allometric relationship between D^2 (cm^2) at breast height and stem volume (cm^3) of *S. macrophylla* at stand density 2100-2300 trees ha^{-1}. (a) linear, (b) exponential, (c) logarithmic, (d) power, (e) quadratic, (f)cubic fitting. The best curve fitted from the cubic equation, here $R^2 = 0.9793$.

Table: 11 Summary results of different regression model of relationship between D^2 (cm^2) and Volume (cm^3) of *Swietenia macrophylla* in medium density plantation (2100-2300).

Regression Model	Regression Equation	R-square Value
Linear	$y = 632.59x - 13443$	$R^2 = 0.9779$
Expon	$y = 23999e^{0.0069x}$	$R^2 = 0.9179$
Log	$y = 100553\ln(x) - 408890$	$R^2 = 0.9163$
Power	$y = 228.94x^{1.1662}$	$R^2 = 0.9694$
Poly 2	$y = 0.1889x^2 + 558.1x - 7777$	$R^2 = 0.9786$
Poly 3	$y = 0.0041x^3 - 2.3265x^2 + 1000.9x - 29629$	$R^2 = 0.9793$

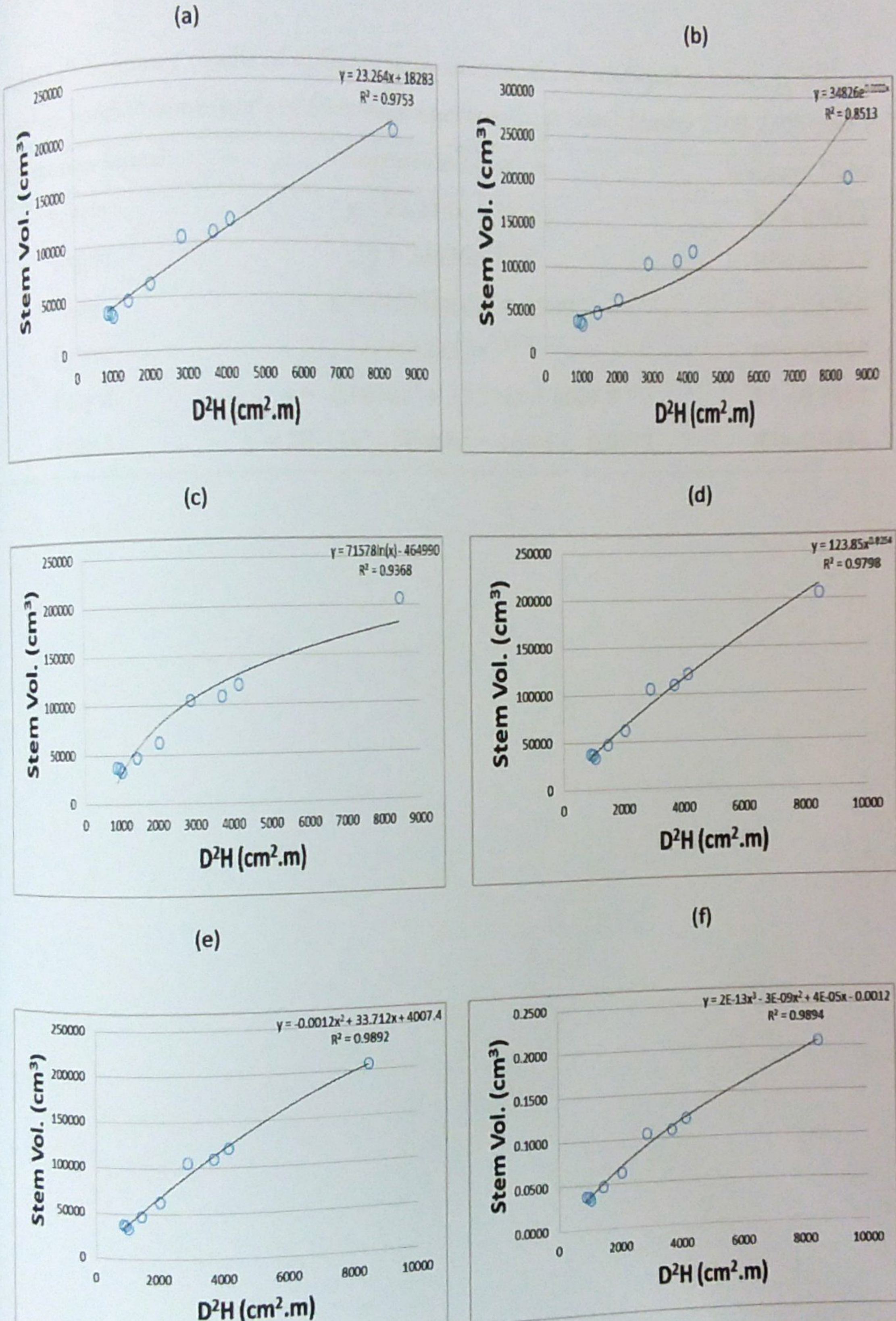


Fig: 13 Allometric relationships between D^2H (cm^2.cm) and stem volume (cm^3) of *S. macrophylla* at stand density 2100-2300 trees ha^{-1}. (a) linear, (b) exponential, (c) logarithmic, (d) power, (e) quadratic, (f)cubic fitting. The best curve fitted from the cubic equation, here $R^2 = 0.9894$.

Table: 12 Summary results of different regression model of relationship between D^2H ($cm^2.cm$) and Volume (cm^3) of *Swietenia macrophylla* at stand density 2100-2300 trees ha^{-1}.

Regression Model	Regression Equation	R-square Value
Linear	$y = 23.264x + 18283$	$R^2 = 0.9753$
Expon	$y = 34826e^{0.0002x}$	$R^2 = 0.8513$
Log	$y = 71578\ln(x) - 464990$	$R^2 = 0.9368$
Power	$y = 123.85x^{0.8254}$	$R^2 = 0.9798$
Poly 2	$y = -0.0012x^2 + 33.712x + 4007.4$	$R^2 = 0.9892$
Poly 3	$y = 2E-13x^3 - 3E-09x^2 + 4E-05x - 0.0012$	$R^2 = 0.9894$

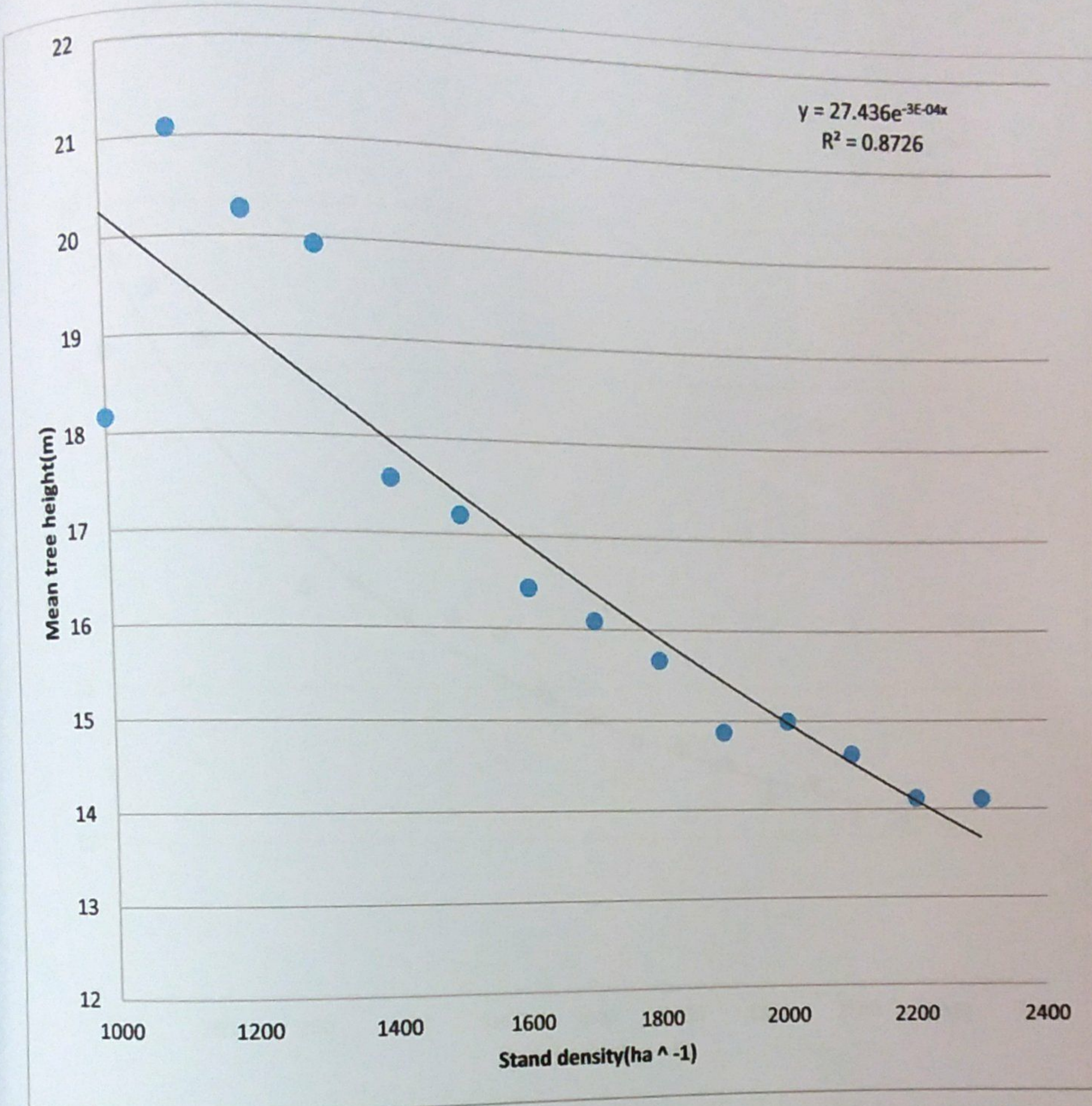


Fig: 14. Relationship between stand density (ha^{-1}) and mean tree height (m). Here, the R^2 value is 0.8726

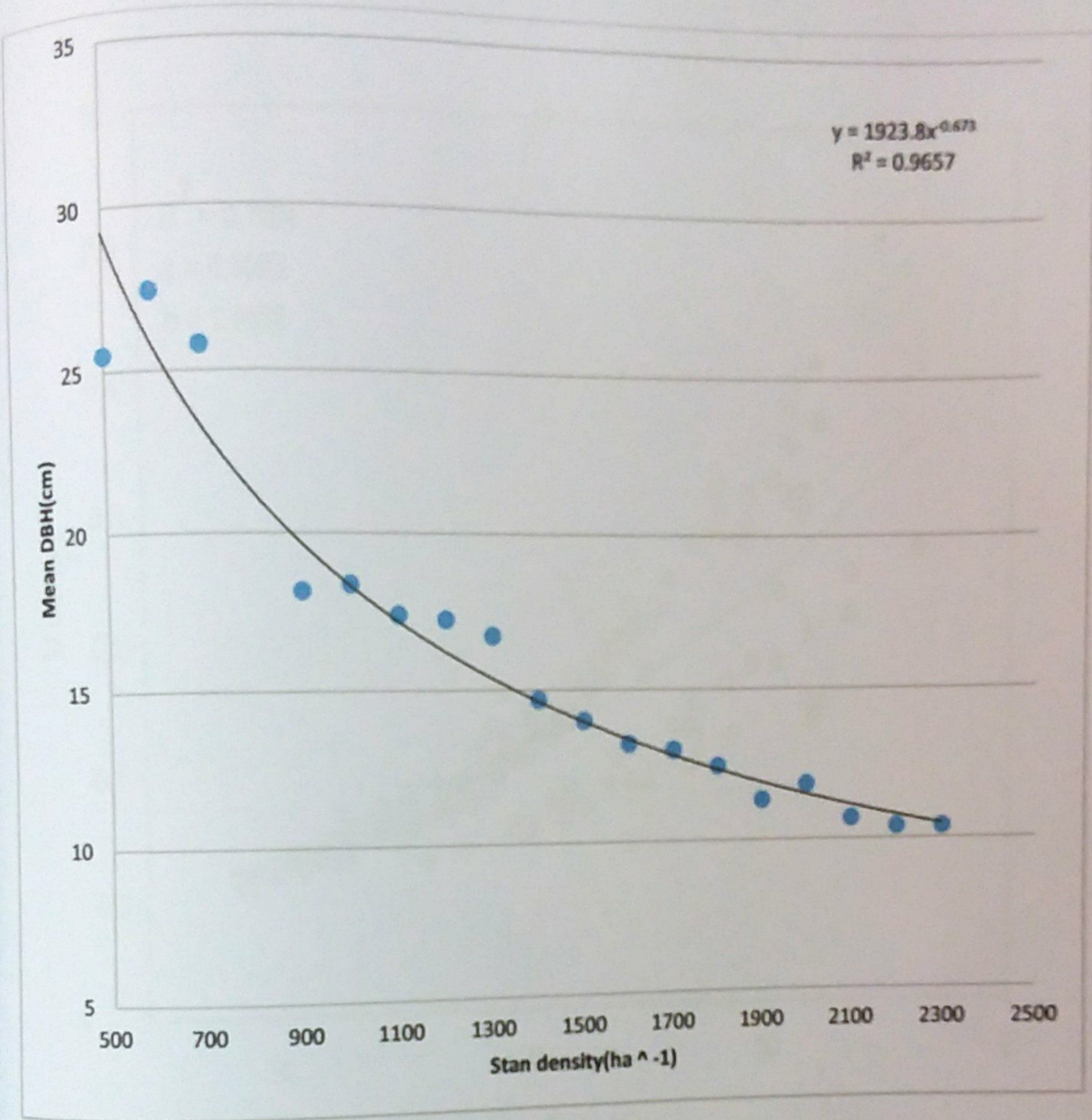


Fig: 15. Relationship between mean tree DBH (cm) and stand density (ha^{-1}). Here, the R^2 value is 0.9657

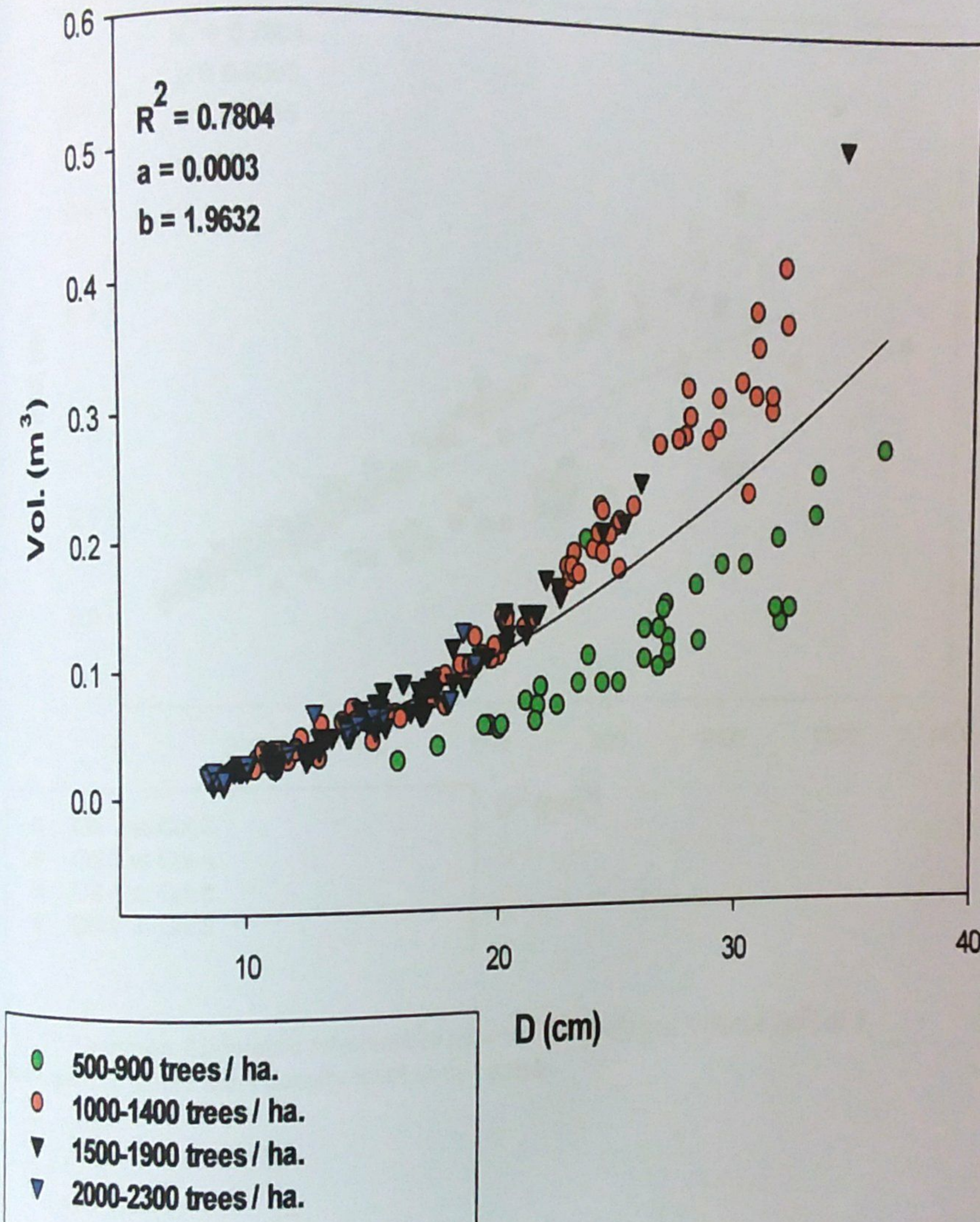


Fig: 16. Common Allometric relationship between D (cm) and Volume (m^3) of *S. macrophylla*. There are 4 density level in this graph.

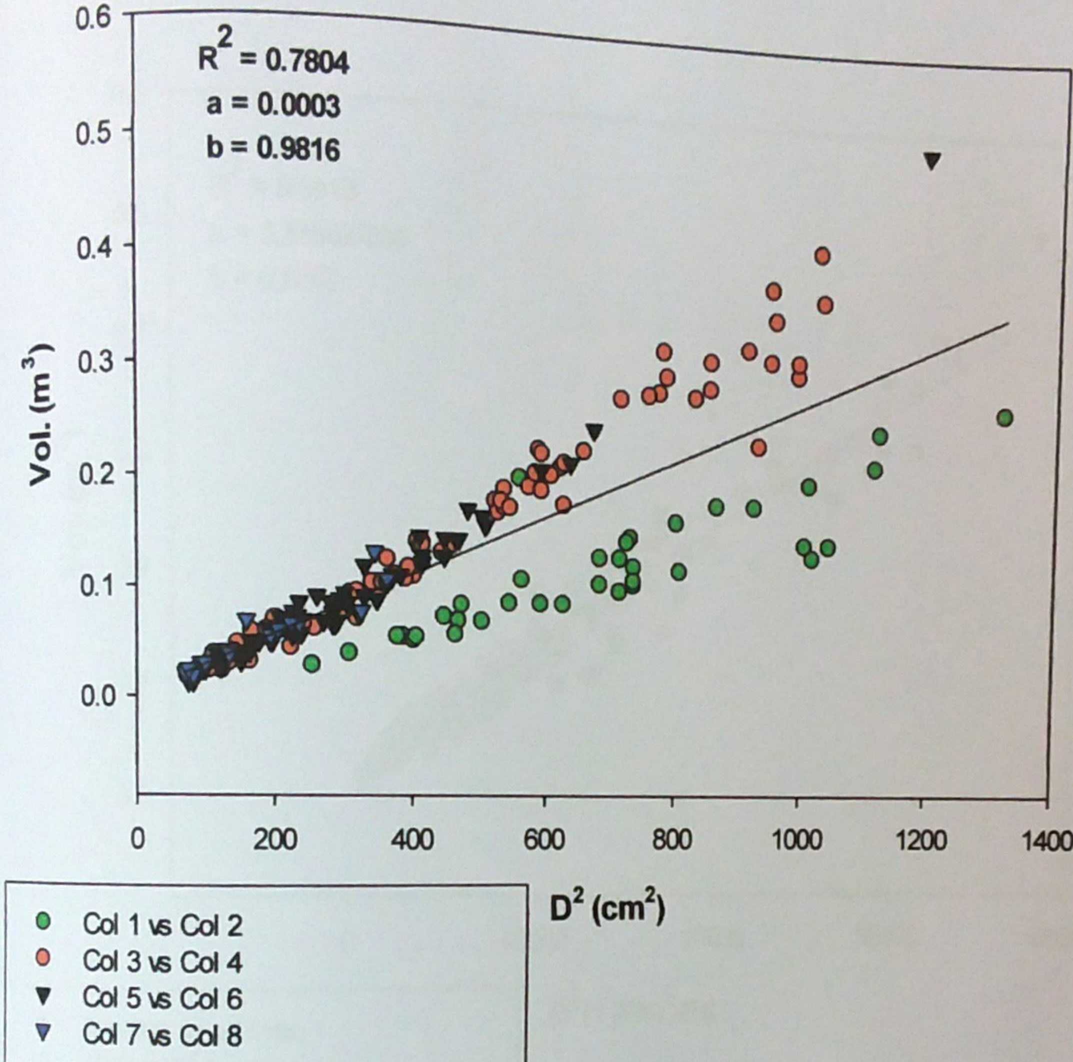


Fig: 17. Common Allometric relationship between D^2 (cm^2) and Volume (m^3) of *S. macrophylla*. There are 4 density level in this graph.

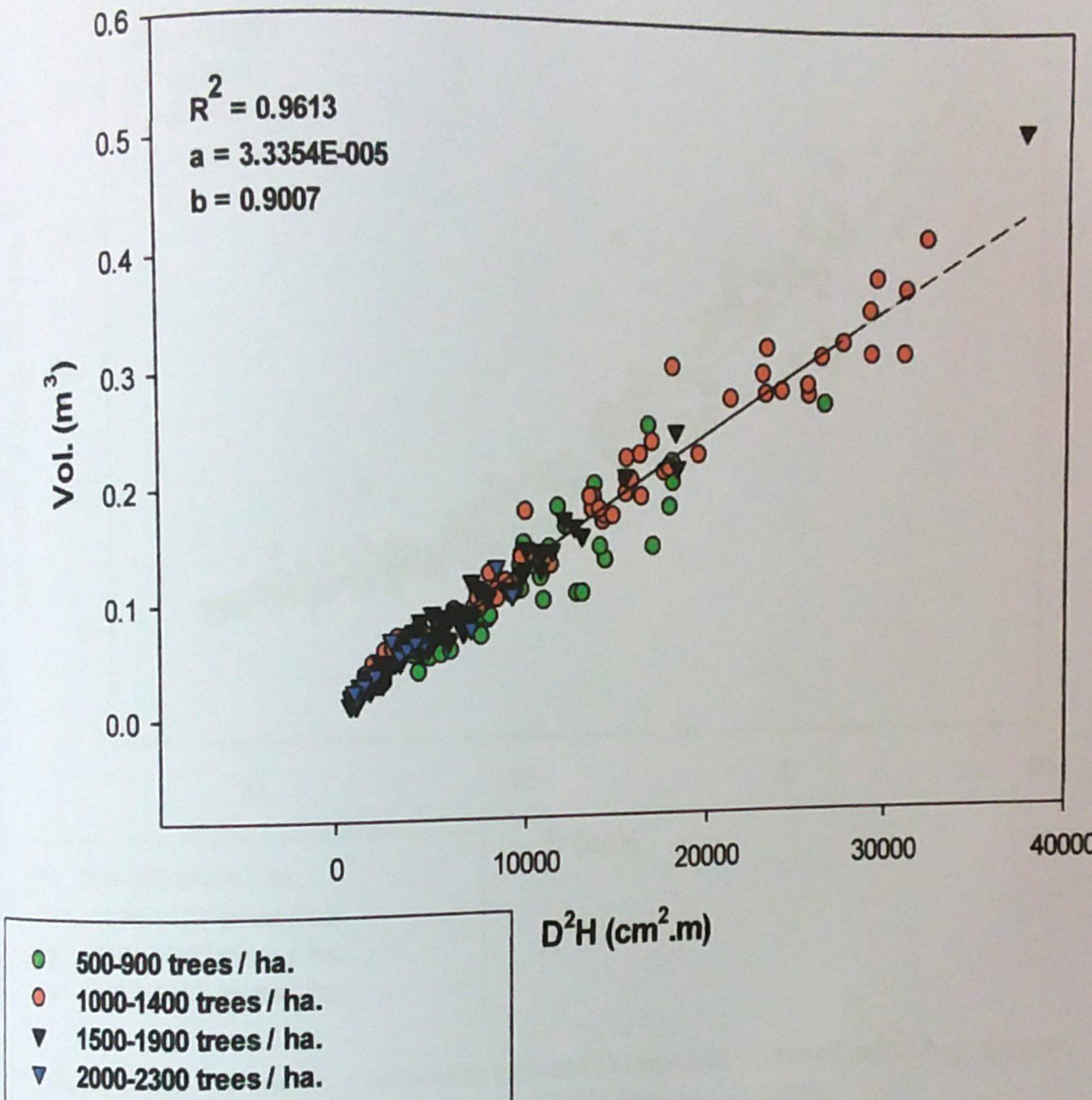


Fig: 18. Common Allometric relationship between D^2H (cm^2.m) and Volume (m^3) of *Swietenia macrophylla*. There are 4 density level in this graph.

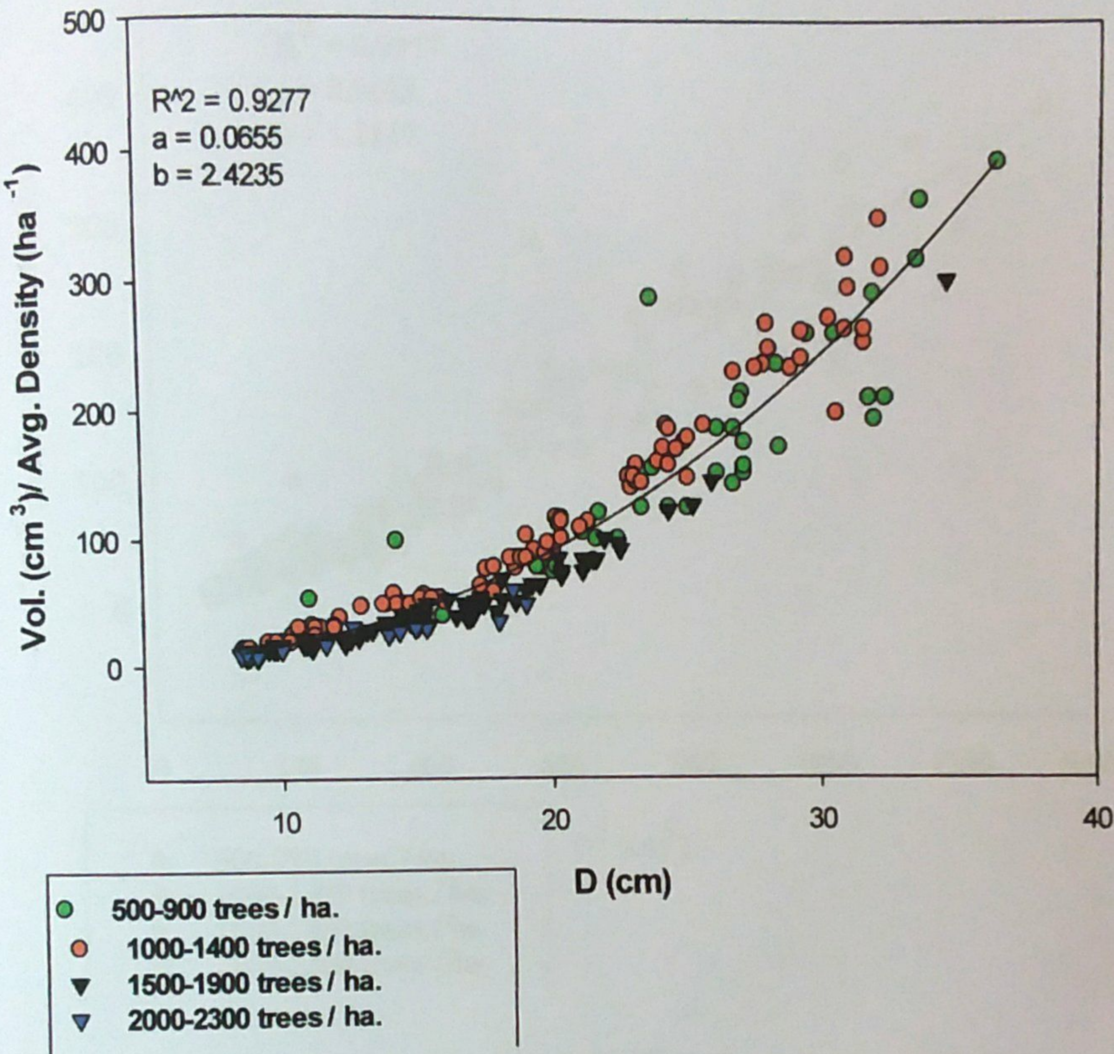


Fig: 19. Common Allometric relationship between D (cm) and Volume (cm^3) / Avg. density (ha^{-1}) of *Swietenia macrophylla*. There are 4 density level in this graph.

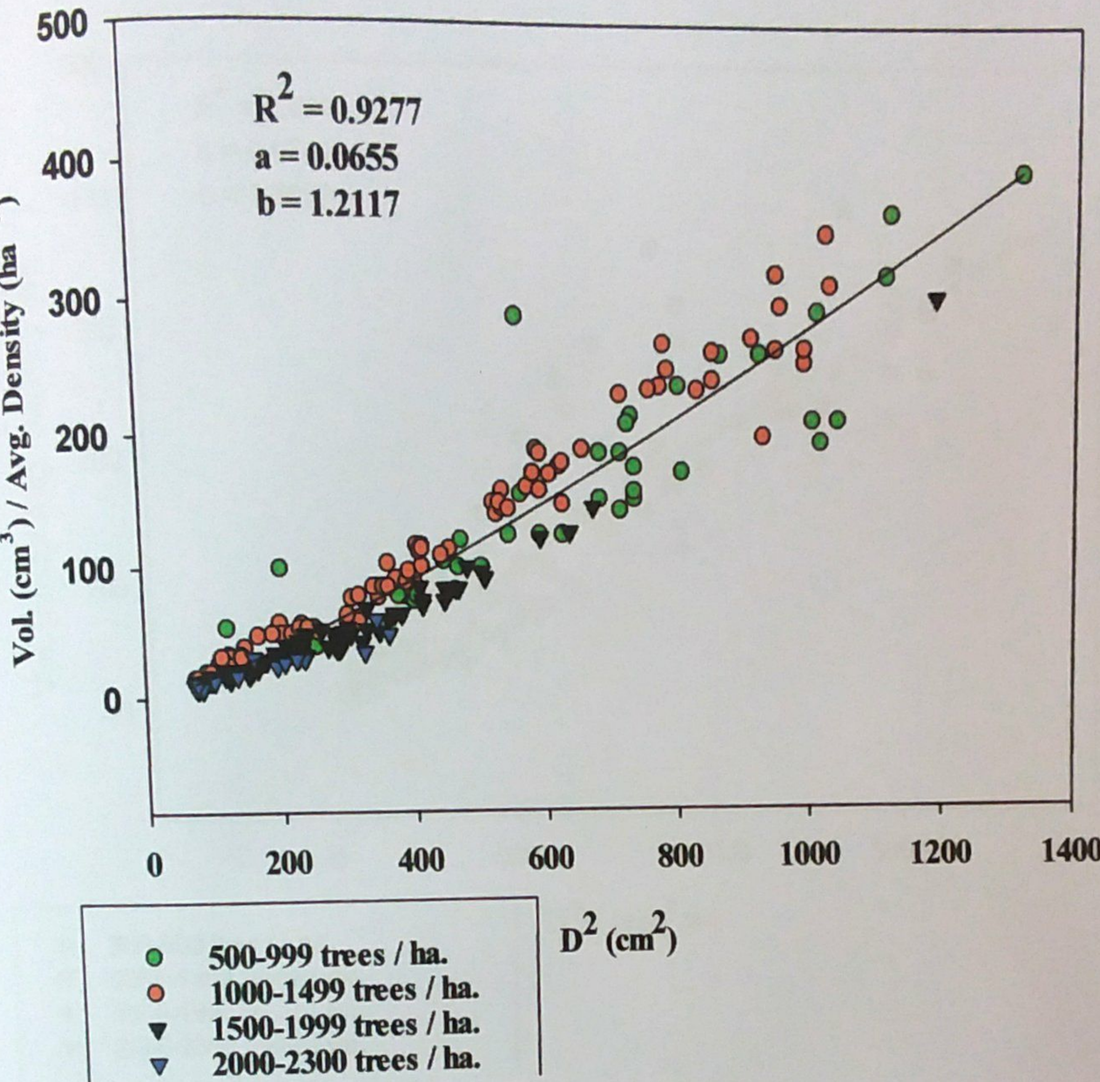


Fig: 20. Common Allometric relationship between D^2 (cm^2) and Volume (cm^3) / Avg. density (ha^{-1}) of *Swietenia macrophylla*. There are 4 density level in this graph.

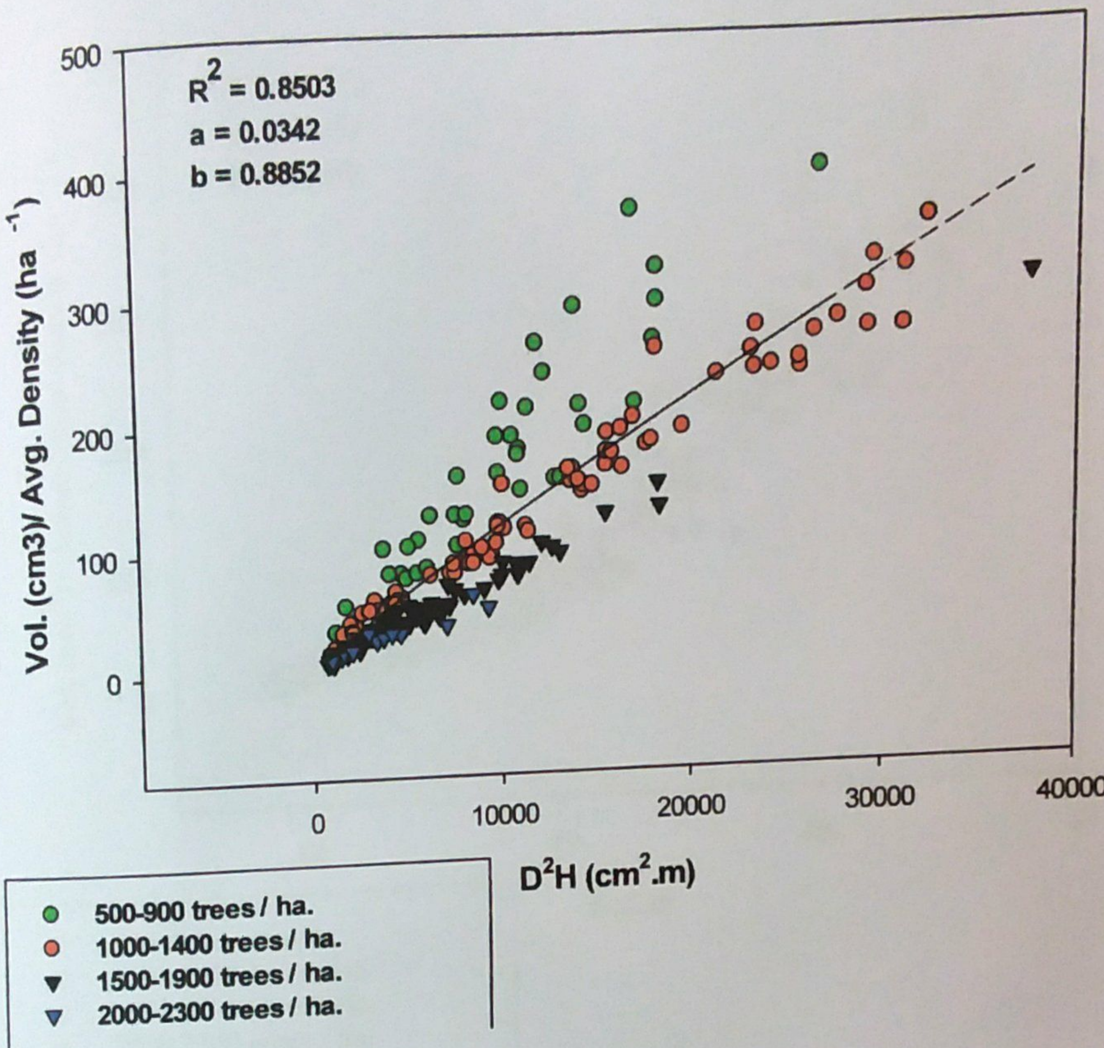


Fig: 21. Common Allometric relationship between D^2H (cm^2.m) and Volume (cm^3) / Avg. density (ha^{-1}) of *Swietenia macrophylla*. There are 4 density level in this graph.

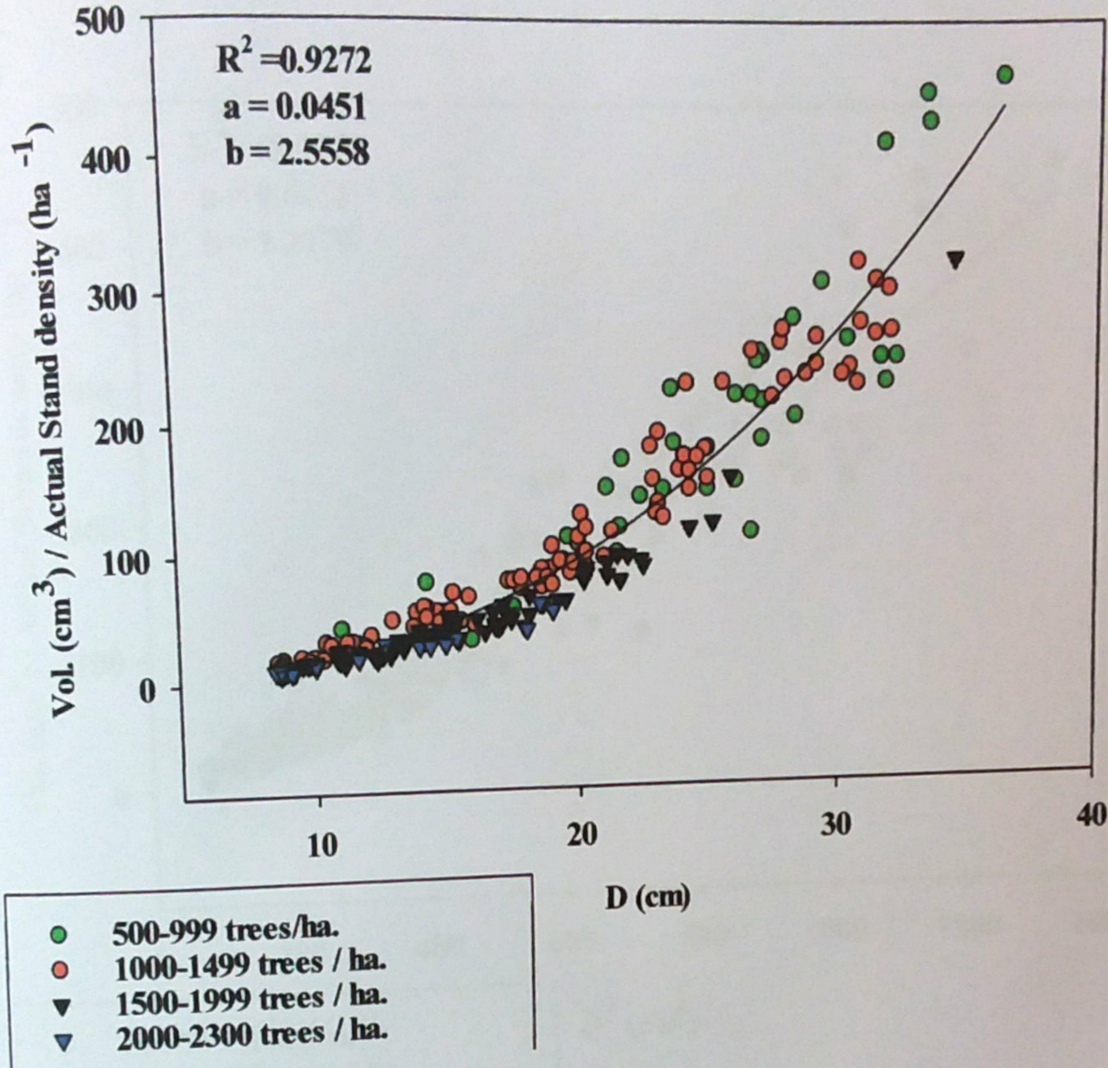


Fig: 22. Common Allometric relationship between D (cm) and Volume (cm^3) / Actual stand density (ha^{-1}) of *Swietenia macrophylla*. There are 4 density level in this graph.

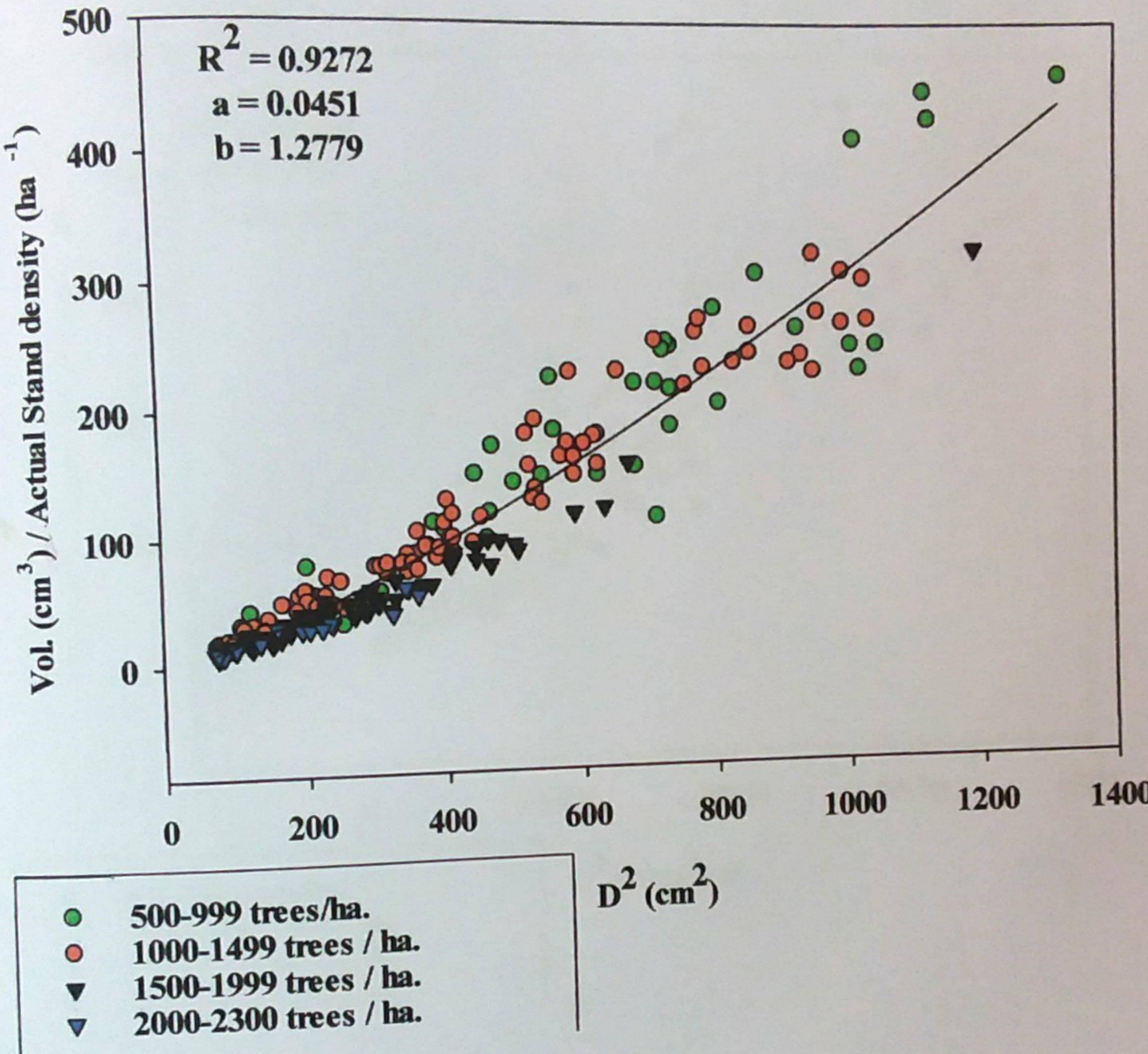


Fig: 23. Common Allometric relationship between D^2 (cm^2) and Volume (cm^3) / Actual stand density (ha^{-1}) of *Swietenia macrophylla*. There are 4 density level in this graph.

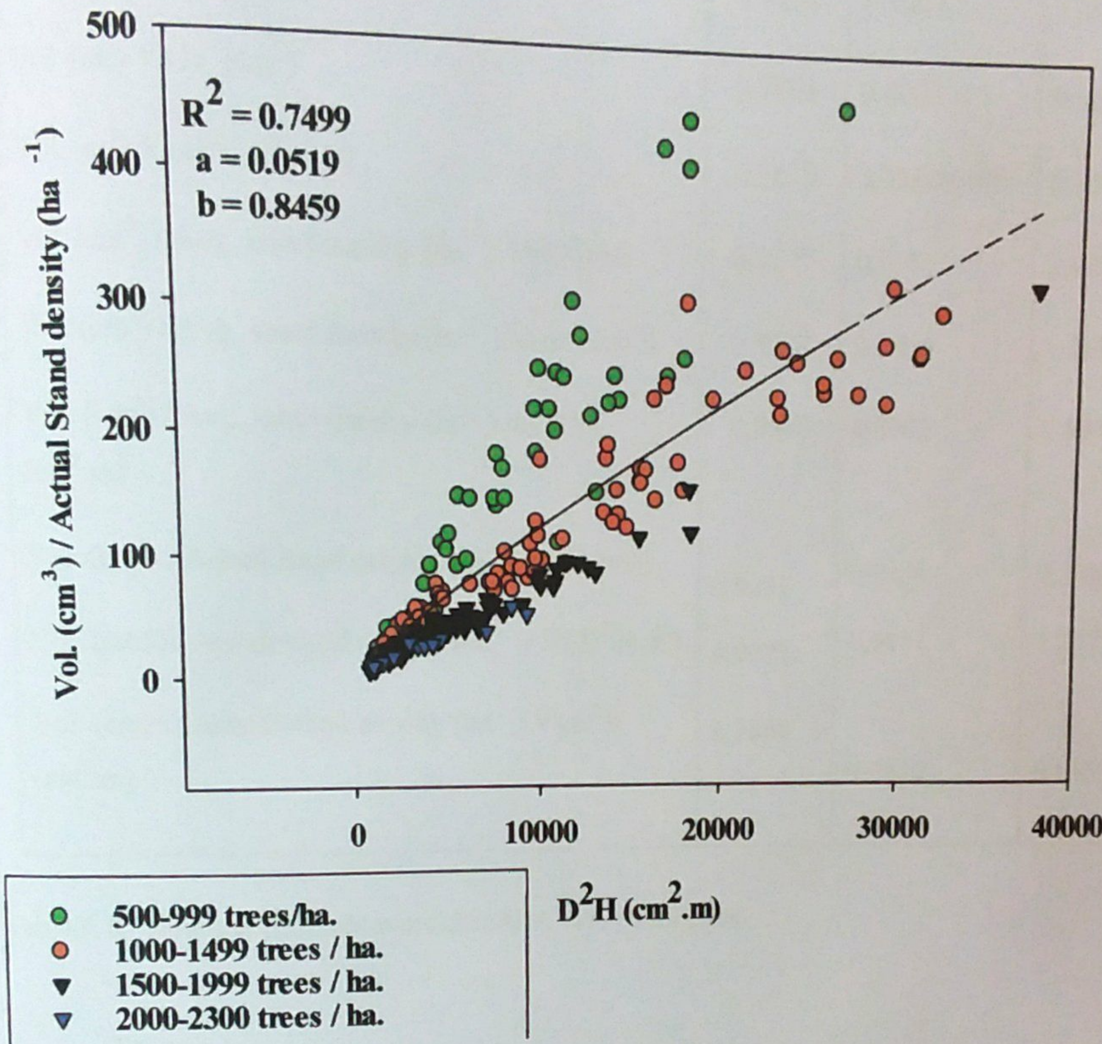


Fig: 41. Common Allometric relationship between D^2H ($cm^2.m$) and Volume (cm^3) / Actual stand. density (ha^{-1}) of *Swietenia macrophylla*. There are 4 density level in this graph.

Equation	R^2	a	b
Vol. (m^3) Vs D (cm)	0.7804	0.0003	1.9632
Vol. (m^3) Vs D^2 (cm^2)	0.7804	0.0003	0.9632
Vol. (m^3) Vs D^2H (cm^2.m)	0.9613	3.3354E-005	0.9003
Vol. (cm^3) / Avg. stand density (ha^{-1}) Vs D (cm)	0.9277	0.0955	2.4235
Vol. (cm^3) / Avg. stand density (ha^{-1}) Vs D^2 (cm^2)	0.9277	0.0955	1.2117
Vol. (cm^3) / Avg. stand density (ha^{-1}) Vs D^2H (cm^2.m)	0.8503	0.0342	0.8852
Vol. (cm^3) / Actual stand density (ha^{-1}) Vs D (cm)	0.9272	0.0451	2.5558
Vol. (cm3) / Actual stand density (ha^{-1}) Vs D^2 (cm^2)	0.9272	0.0451	1.2779
Vol. (cm3) / Actual stand density (ha^{-1}) Vs D^2H (cm^2.m)	0.7499	0.0519	0.8459

Tab:13. R^2 values at different stand densities with parameters.

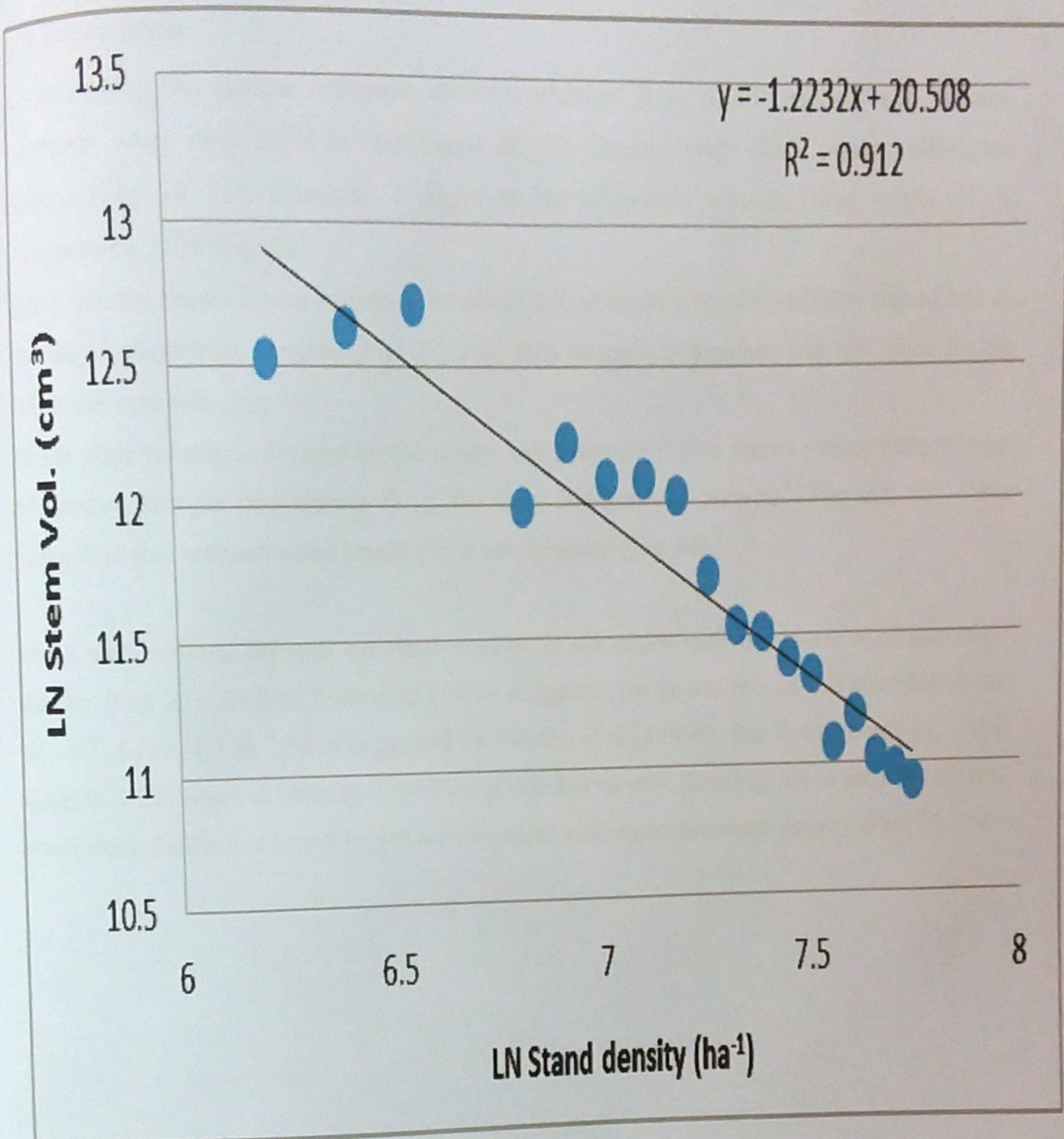


Fig: 22. Relationship between stand density (ha^{-1}) and mean stem volume (cm^3). Here, the R^2 value is 0.91 which derived from logarithm formula and slope of the line is -1.22.

4.2 Discussion

Stand density has greater influence on stem volume. It is closely related with volume. However, when only DBH is considered all the density levels show weaker allometric relation (Fig: 16, 17). However, it improves the allometric strength when height (H) is incorporated, D^2H (Fig: 18)

Stand density shows strong influence on allometric strength when DBH (D) is considered as the only independent variable (Fig: 19, 20). This strength is however reduced when height (H) is incorporated (Fig 21).

When stem volume is divided by the actual stand density it also shows strong influence on allometric strength considering D as the only independent variable (Fig: 22, 23). This strength is also reduced when height (H) is incorporated (Fig 24).

Mean stem volume depends on stand density. It decreases with the increase of the stand density (Fig: 25). At first Yoda et al.(1963) suggested the power law of self-thinning -1.5o, i.e.,-3/2. Later -4/3 or 1.33 is suggested by Enquist et al., (1998). But in this study the value slope is -1.22, which is close to -4/3 of the power law of self- thinning. Mean stem height and mean stem diameter at breast height are decreased with increased stand density (Fig: 14, 15).

Chapter Five

Conclusion

5.1 Conclusion:

Allometric relationships of stem volume at various stand density in *Swietenia macrophylla* King was investigated. In this investigation diameter at the breast height (D) was found as the most independent variable when specific stand density was considered. However height was found as the independent variable average or actual stand density was not corporated. Incorporation of the stand density shows that it is a conspicuous effect of stand density for stem volume estimation.

As trees are growing larger, the space density among themselves being narrow and they start to compete among them. Some individuals die for acute competition which is called self-thinning. There should be a proper stand density to get a handsome volume in small time. The slope of self-thinning is directed related with volume and stem diameter at breast height point. Further research can be performed to get a optimum stand density for maximum volume production using data from known stand age, which is not available for this study.

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