Effect Of Relative Humidity, Species and Extractives on the Equilibrium Moisture Contents of Some Hardwood Species Growing in Sudan

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الرطوبي

المتوازن في بعض الأنواع الشجرية الصلدة التي تنمو في السودان

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DEDICATION

To the soul of my Father,

to my dear mother and

to my beloved brothers and sisters

ACKNOWLEDGMENT

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ABSTRACT

Effect of Relative Humidity, Species and Extractives on the Equilibrium Moisture Content of Some Hardwood Species growing in Sudan

This study was conducted to investigate the variation between hardwood species in their responses to of relative humidity changes and hot water extraction.

Six wood species (*Acacia nilotica, Acacia senegal, Anogeissus leiocarpus, Boswellia papyrifera, Ailanthus excelsa* and *Calotropis procera*) growing in Northern and Southern Kordofan States were selected. For each species, wood samples were collected from six trees, from which specimens (1.5x 3.5x 5 cm) were prepared.

Equilibrium moisture content was determined for these specimens at different relative humidities (0-95%) using various saturated salt solutions. The specimens were placed in a closed deisccator, which contained a saturated salt solution and then kept inside the oven at the specified temperature (60 and 90 C) until the equilibrium moisture content was obtained. The effect of extractives was study by comparing the equilibrium moisture content of extracted (hot water extraction) and unextracted wood.

Desorption and adsorption isotherms of the six wood species exhibited sigmoid curves. The statistical analysis indicated a direct relationship between equilibrium moisture content and relative humidity that can be well explained by linear equation and third-order polynomial equations. There were significant differences in the equilibrium moisture content between species. At low relative humidities differences appear to be minimal, but at higher humidities difference remarkably among species are significant. The effect of extraction was significant at a few relative humidity values in some species; unextracted wood had higher equilibrium moisture content than extracted wood.

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بسم الله الرحمن الرحيم

ملخص الأطروحة

أثر الرطوبة النسبية والأنواع الشجرية والمستخلصات الكيميائية علي المحتوي الرطوبي المتوازن في بعض الأنواع الشجرية الصلدة التي تنمو في السودان

تهدف هذه الدراسة للتعرف علي أثر كل من الأنواع الشجرية و الرطوبة النسبية ودرجة الحرارة علي المحتوي الرطوبي المتوازن للأخشاب، و كذلك معرفة أثر وجود المستخلصات علي خاصية الإسترطاب في بعض الأخشاب السودانية الصلبة. تم جمع ستة أنواع شجرية (سنط، هشاب، صهب، إيلانسس، قفل و عشر) من ولاية شمال و جنوب كردفان، ومن ثم تم تجهيزها و تقطيعها الي أبعاد $1.5 \times 3.5 \times 5$ سم ثم لفها جيداً في أكياس ووضعها داخل ثلاجة حتي لا تفقد شيء من رطوبتها والاحتفاظ بها خضراء لحين استخدامها في التجربة. تم تحديد المحتوي الرطوبي المتوازن للأخشاب وذلك بوضع ستة عينات من كل نوع شجري داخل desiccator يحتوي علي محلول ملحي يعطي الرطوبة النسبية المطلوبة. ثم أخذت ثلاثة عينات من كل نوع شجري و تم تجزئتها ألي رقائق و قسمت الي مجموعتين. الأولي أزيلت منها المستخلصات الكيميائية و الثانية تركت كما هي ثم تم تحديد المحتوي الرطوبي المتوازن لها.

أوضح التحليل الإحصائي أن هنالك علاقة موجبة (طردية) بين المحتوي الرطوبي المتوازن والرطوبة النسبية بينما كانت العلاقة سالبة (عكسية) بين المحتوي الرطوبي المتوازن و درجة الحرارة. كذلك أوضحت النتائج أن هنالك اختلاف معنوي بين الأنواع الشجرية و أن العلاقة بين المحتوي الرطوبي المتوازن و الرطوبة النسبية كانت علي شكل الحرف S .

من ثم أثبتت الدراسة أن العينات التي لم يتم إزالة المستخلصات منها كانت ذات محتوي رطوبي أعلي من تلك التي تم استخلاصها

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CHAPTER I

INTRODUCTION

BACKGROUND

Water is a natural constituent of all parts of a living tree. Freshly cut wood may have a large amount of water varying from 30 % to more than 200 %, depending on species. The water has a profound influence on the properties of wood, affecting its weight, strength, shrinkage and liability to be attacked by some insects and fungi that cause stain or even decay.

The moisture content is measured for fresh or air-dry wood and expressed as percentage of the oven dry weight Skaar (1972).

The moisture in wood is found in two forms: bound water and free water. Bound water is the water adsorbed in the cell wall.   This is limited to approximately 30 percent of the oven dry weight of the wood. Desch and Dinwoodie (1981) reported that in most timbers the walls could hold about 25% to 30% of their dry weight. This implies that the wood is at fiber saturation point. Free water is the water or sap, present in lumens or cell cavities. The porosity or fractional void volume of the wood limits the quantity of the free water present in wood (Siou 1971).

The Molecules of water are constantly leaving and returning to the wood surface. If the same numbers of molecules of water returns and leaves from the wood surface, an equilibrium condition exists. Since the wood

is either gaining or losing water it is said to have reached equilibrium moisture content. Hence, the equilibrium moisture content is the bound water fraction of a wood specimen, which is in equilibrium with the surrounding air. Its value increases with increasing relative humidity and decreases with decreasing temperature.

As a hygroscopic material, wood naturally takes on and gives off water to balance out with its surrounding environment. Wood must be dry, to avoid exposure to shrinkage and swelling. Knowing the equilibrium moisture content values at different relative humidities and temperatures is essential to determine the target wood moisture content for both air and kiln drying of wood.

The equilibrium moisture content varies among wood species, between heartwood and sapwood of the same species and with the extractive content of the wood. It is also affected by temperature, mechanical stress, and by the previous exposure history of the wood Skaar (1972). Differences between species may be anticipated on the basis of differences in chemical composition. Skaar and Kelsey (1958, 1959) found substantial differences between hemicelluloses, cellulose, and lignin in hygroscopicity. Such differences, coupled with variations in crystalline cellulosic content or in cell wall density, are expected to result in variations in hygroscopicity.

It is hypothezised that there are variations in the equilibrium moisture content between species due to response of the wood moisture to variations in relative humidity and temperature;

OBJECTIVES

This study is designed to investigate the variation in equilibrium moisture content between different species in response to differences in relative humidity and temperature of the surrounding air.

The specific objectives were:

- To study the effect of relative humidity (0 –95%) and temperature (60 and 90 ˚C) on equilibrium moisture content.

- To determine desorption and adsorption isotherms of the equilibrium moisture content for six Sudanese hardwood species.

- To study the variation between species in the isotherm of the equilibrium moisture content

- To study the effect of removing extractives on the hygroscopicity of wood.

Sudanese hardwood species show great variation in their extractive content and density (Mohammed 1999; Mahgoub 2001).

Research on such species is different, therefore there is strong need to assess the equilibrium moisture content which is important as basis for seasoning purposes, as well as in many wood-based industries.

CHAPTER II

LITERATURE REVIEW

DESCRIPTION AND DISTRIBUTION OF THE SELECTED SPECIES

Six hardwood species of various densities were used in this study, namely: *Acacia nilotica* sub species *tomentosa* (Sunt), *Acacia senegal* (Hashab), *Anogeissus leiocarpus* (Sahab), *Boswellia papyrifera* (Gafal), *Calatropis procera* (Ushar), and *Ailanthus excellsa* (Ailanthus).

The first three species have high-density wood while the other species have low-density wood (Mohmoud 2001, personal communication).

All species grow in North and South Kordofan States, their descriptions and distribution are given in the following sections.

Acacia nilotica
Description

Trees which are 5-15 m high (El Amin 1990) or 2.5-14 m high (Sahni 1968), have dark grey, brown or black, rough and fissured bark. The stipules are spinescent, straight white pubescent, 1-8 cm long. The leaves are 2-7 cm long, petioles glandular 1-3 pinnate. The fruits variable pods are straight or slightly falcate, 5 - 20 x1.2 cm, ridged, dark brown to dark grey with 10-12 seeds per pod; the surface is ridged, venation longitudinal or not apparent. Seeds are dark brown or brownish-black, elliptic to sub-circular 8mm; areola marginal, U-shaped or closed

O-shaped, funicles 3 mm long, thin brown (El Amin 1990). The wood is hard, heavy and durably, although not completely resistant to termites (heartwood connot be impregnated).

Distribution and Habitat

Acacia nilotica species comprises the following four sub species (El Amin 1990):

* *Acacia nilotica* sub species *nilotica*

* *Acacia nilotica* sub species *tonemtosa*

* *Acacia nilotica* sub species *adansonii*

* *Acacia nilotica* sub species *subalata.*

However, the fourth one (subalata) is of doubtful occurrence in the southern Sudan (Sahni 1968).

The sub species chosen for this work *Acacia nilotica* sub species *tonemtosa* is distributed in the North area, South area, and Central Sudan (El Amin 1990). In Blue Nile area, Rosaries, is about the Southern boundary. However, it is also encountered along "wadis" as far south as Khor Tumbak 10 N. Latitude. On the main Nile, the best forests are along the Blue Nile south of Sennar where old meander channels of the river have been cut off to form shallow basins (Sahni 1968).

Sub species *tomentosa* habitat is mainly along banks of the Nile and its tributaries, on light silty soils (El Amin 1976).

Acacia senegal
Description

Bush or tree usually less than 6 m, sometimes up to 12 m high (Sahni 1968) and shrubs or small trees 2-12 m high (El Amin 1990). Bark yellow to light brown or grey, rough, fissuring or flaking. Stipules not spinescent, prickles at nodes in threes ; 2 lateral pointing upward or forward and one central pointing downwards or backward, falcate, 4-7 mm long (El Amin 1990; Sahni 1968). Inflorescence flowers cylindrical, spike 2–10 cm long, spike usually longer than leaves and flowers are white or cream. Pods pale brown to straw coloured, flat and papery, usually 9 cm long, rounded to acuminate (Sahni 1968).

Seeds 8-12 mm in diameter, yellow or pale brown, compressed. Flowering November-February; fruiting January-April (El Amin 1990; Sahni 1968). The wood is used for firewood, charcoal and local building purposes.

Distribution and Habitat

It has two main areas of distribution: on stabilized sands, under rainfall of 280-450 mm per annum or on the dark cracking clays under rainfall of 500 mm per annum (Sahni 1968). It is widespread on sandy and clay plains of savanna grasslands (El Amin 1976).

Acacia senegal is distributed in Southern Nuba, from Barber to Mongala in Blue Nile, Kassala and Kordofan (Sahni 1968). The species is

encountered at central Sudan along a continuous belt extending from east to west, but it is more successful on the Western sand plains of Kordofan and Darfur (El Amin 1976).

Anogeissus leiocarpus
Description

Medium sized to large tree up to 20 m high. Bark greyish white, becoming very dark grey in old trees, fairly smooth, flaking off, branches often drooping and slender. Leaves alternate, rarely opposite or subopposite, elliptic to ovate lanceolate, 2-8 x 1.3 5 cm densely silky becoming pubescent beneath (El Amin 1990) or 2 – 8 cm long, 1.2-3.5 cm broad, at first densely silky, then laxly pubescent beneath, leaves light green or ash coloured (Sahni 1968). Flowers in globose heads, small, greenish yellow, with a reddish disk with white hairs, petals absent. Fruit in globose cone – like heads, broadly winged coriaceous, dark grey about 3-mm broad, beaked by the persistent receptacle (El Amin 1990; Sahni 1968). Valuable timber. Sapwood quite large, yellowish nearly black, hard.

Distribution and Habitat

Et is widespread in Kassala, Kordofan, Darfur, Bahr el Ghazal and upper Nile States. In Equatoria States, the species is absent from the east banking of the Nile except for a small area within 20 km of Juba. In Yambio district, it occurs in the gallery forest. Specimens from drier

areas tend to have smaller leaves and more hairy flowers (El Amin 1990; Sahni 1968).

Boswellia papyrifera
Description

It is a deciduous savanna tree up to 10 m high. Bark pale yellow brown, papery, peeling in strips; slash reddish, exuding fragrant resin. Leaves, which are soon deciduous, are 30 cm long (Vogt 1995; El Amin 1990; Sahni 1968). Leaflets 13-19 (Sahni 1968) or 13-10 (El Amin 1990) pairs, sessile, opposite or subopposite, crenate, oblong-lanceolate, up to 12.5 x 4.5-cm inflorescence panicles 3- 45 cm long, clustered at ends of thick branches (El Amin 1990; Sahni1968). Flowers white – creamy, tinged with pink, appearing before the leaves, sweet scented on red peduncles. Fruit capsular red (Sahni 1968) or brown pink 3–(rally 4) sided (El Amin 1990), pear – shaped 2.5 cm long with short vertical wings. Flowering March – April, fruiting May (El Amin 1990; Sahni 1968). The wood from this tree is yellowish- white, fine-grained and hart it is provides a good quality firewood and charcoal.

Distribution and Habitat

Boswellia papyrifera is found on rocky ground in high rainfall savanna in Bule Nile State (Jebel Garri), Kordofan State (Nuba Mountains), Darfur State (Zalingi, Radom, Jebel Marra) and in Southern Sudan on quartzitic soils (Vogt 1995; El Amin 1990; Sahni 1968).

Ailanthus excelsa
Description

Trees are 20–24 m high (Vogt 1995) or 20 m high (El Amin 1990). Bark is white grey, smooth with large conspicuous leaf scars, granular and greyish brown in old trees. Leaves up to 1-m long, leaflets 8-14 pairs, lanceolate or ovate lanceolate, 5-15 x 4.5 cm, margin 3-4 toothed towards base. Inflorescence panicles of yellow flowers, 20 cm long. Fruit 1 seeded light brown or yellow samaras. Flowers Jan-March, fruit March (Vogt 1995; El Amin 1990). The timber is not high quality, but is easily worked and therefore made into clrums, cigar boxes, cases, toys, boats and tool handles.   .

Distribution and Habitat

The species was introduced from the Indian peninsula and planted in many semi-arid moist regions of central Sudan on river alluvium and sandy loams (El Amin 1990).

Calatropis procera
Description

It is Shrubs or small trees up to 6 m high. The bark is thick or corky and yellow-brown in colour. The young parts covered with white powdery tomentum (Vogt 1995; El Amin 1990). Leaves opposite- decussate, pale green, succulent, sessile or shortly pentiolate, ovate or obovate,
6-30 x 4-17 cm, hairy, together with branches exuding milky latex (El Amin 1990). The flowers arise from the base of the leaves in clusters of

3-10 and are white to purplish in colour. Green, spongy fruits provide an easy means of recognizing this plant. All parts of the plant exude white milky latex when cut (Vogt 1995 and El Amin 1990). The strong inner bark fibers produce a binding material and are processed into fabrics. When cultivated, yields of up to 500 kg of fiber per hectare and year are expected. The inner bark is stripped, soaked in water for 1-2 days and dried.

Distribution and Habitat

The species is found throughout the Sudan in disturbed areas and near villages (El Amin 1990).

Definition of Equilibrium Moisture Content (EMC)

Skaar (1972) and Haygreen and Bowyer (1989) have reviewed sorption from the molecular standpoint. Water is believed to be hydrogen-bonded to the hydroxyl group of the cellulosic and hemicellulosic portions of wood. Not all hydroxyl groups are accessible to water molecules because the hydroxyl groups of adjacent cellulose molecules in the crystalline regions hold each other, allowing the formation of weak cellulose-to-cellulose bonds. When water return, fewer sorption sites are available for water than was the case originally.

Various workers defined the equilibrium moisture content as the moisture content that wood will attain at equilibrium when exposed to a given humidity and temperature. Siau (1971) defined equilibrium

moisture content as the bound water of a wood specimen, which is in equilibrium with the surrounding air. Its value increases with relative humidity and decreases with temperature.

Equilibrium moisture content is the particular moisture content of the wood that is in equilibrium with its surrounding environment (Desch and Dinwoodie 1981). Brooker *et al.* (1992) defined equilibrium moisture content as the moisture content at which the internal wood vapor pressure is in equilibrium with the vapor pressure of the environment.

A piece of wood is in equilibrium moisture content with its environment when the rate of moisture loss from the wood to the surrounding atmosphere is equal to the rate of moisture gain of wood from the surrounding atmosphere (Hall, 1957).

Equilibrium moisture content values for various temperatures and humidities, first published at Forest Products Laboratory in 1919 by Koehler, have been successfully applied to most North American species. But, because moisture moves in wood very slowly, the equilibrium moisture content values are useful for predicting the moisture content only for small samples (1 cm or less thick) in the flow direction. When larger samples are exposed to dynamic environment, they may never reach equilibrium but will continually have internal moisture gradients (Wengert, 1976).

Factors Affecting the Equilibrium Moisture Content

There are a number of factors affecting the equilibrium moisture content.

Skaar (1972) reported that the equilibrium moisture content is affected

by the relative humidity, temperature, mechanical stress and by the

previous exposure history of the wood. He noted that it also varies

somewhat among different wood species, between heartwood and

sapwood of the same species, and with the extractive content of the

wood. The detailed effects of some of these factors will be discussed in

the following sections.

Effect of relative humidity

Siau (1971) and Skaar (1972) reported that the single most important

factor that influences the equilibrium moisture content of wood is the

present relative humidity or relative vapor pressure of the surrounding

atmosphere. Chen, *et al.* (1995) reported that the effect of relative

humidity on the equilibrium moisture content of litchi was greater than

that of temperature

The accurate measurement of relative humidity is difficult because the

mass of water per unit volume of air is small. The wet and dry bulb

hygrometer has an accuracy of about ±3%. The extent of the

evaporation and therefore the cooling which takes place around the wet

bulb temperature, is directly related to the relative humidity and

temperature of the room, and the movement of the air around that bulb (Gough, 1974)

Effect of history

Desch and Dinwoodie (1981) stated that the factor with the greatest influence on the equilibrium moisture content, however, is the past history of moisture content levels in the wood.

The curve relating the moisture content of wood with the relative humidity at a constant temperature is called sorption isotherm.

An isotherm is defined as that curve resulting from plotting the moisture content values on the ordinate (y-axis) and the respective relative humidities on the abscissa (x-axis). These equilibrium relationships are obtained at a constant specified temperature.

The isotherm may be of desorption or adsorption equilibrium moisture content depending on whether water was removed or added, respectively. For the determination of sorption isotherms it is necessary to provide a number of relative humidity conditions at a temperature to which samples are exposed until they reach their equilibrium moisture content (Suchsland 1980). Zang *et al.* (1992) stated that adsorption and desorption isotherms have important effect on the drying and storage of crop products.

The relationship between the relative vapor pressure in the environment and the moisture content of wood in equilibrium with that environment is

not linear. This results from the three different ways in which bound water is held. The graph of this relationship at a constant temperature is called a sorption isotherm, which is typical of most species and most wood products. This means that if a piece of wood has desorbed to an equilibrium point, it may attain a moisture content as much as 3% higher than if it had adsorbed at the same relative vapor pressure. Above a relative vapor pressure of a bout 0.5 the initial desorption curve of green wood is slightly above that of a previously dried piece. It follows that for any condition of relative humidity and temperature the equilibrium moisture content attained during desorption is greater than the equilibrium moisture content attained during adsorption from the dry condition. The differences between desorption and adsorption curve is referred to as hysteresis or lag effect (Haygreen and Bowyer1989). Hysteresis is common to many types of physicochemical phenomena. In green condition, the hydroxyl groups of the cellulosic cell wall are satisfied by water molecules, but as drying occurs these groups move closer together, allowing the formation of weak cellulose-to-cellulose bond. When adsorption of water then occurs, fewer sorption sites are available for water than was the case (Skaar 1972). Not all researchers have been able to observe that the hysteresis loop is closed at the upper end as illustrated by Wangaard and Grandos 1967. Browning in 1967 stated that a closed hysteresis loop is obtained only when desorption data

are observed after adsorption data. Various types of sorption isotherms were presented in the literature.

Brooker *et al.* (1992) noted that the S-shaped or sigmoid isotherm as being characteristic of all biological products including cereal grains. Five general types of sorption isotherms have been identified for various gas solid systems (Simpson 1979). These are summarized as follows:

The type 1 isotherm is characteristic of sorption where a layer of vapor only one molecule thick is formed on the solid. Type 2 sorption is characteristic of sorption where more than one layer of vapor is formed on the solid and where the forces of attraction between the vapor and solid are large. (Wood exhibits this type of sorption). Type 3 sorption is similar to type 2 except that the forces between the vapor and solid are relatively small. Types 4 and 5 characterize the case in which the ultimate amount of adsorption is limited by capillary condensation in rigid capillaries.

Sheng (1989) stated that the dynamic method was used to measure the equilibrium moisture content of peanuts. Kernels and hulls could reach the equilibrium within 1 day while pods needed 5 days. Hysteresis between the sorption isotherms was evident from experimental data. Most of the hysteresis values were less than 10%. Good linear relationship between the hysteresis values and desorption equilibrium moisture content was found.

Also, Avramidis (1989) reported that four sorption isotherm models that express moisture content as a function of both relative humidity and temperature were evaluated by fitting them to a set of sorption data between 21.1 and 71.1 °C, with the help of a nonlinear curve-fitting program. All of these models predicted the sigmoid shape of the sorption isotherms and the shift towards the x-axis as the temperature increased. Verma and Gupta (1988) and Chen *et al.*(1995) determined adsorption and desorption equilibrium moisture content isotherms of sugarcane bagasse were determined using static methods at various temperatures (30-90 °C) and relative humidity levels (25-90%). Though the curves were similar to those for food grain, the numerical values of equilibrium moisture content of bagasse were lower than those most grains at corresponding temperature and relative humidity conditions.

Hossain and Bala (2000) reported that the adsorption and desorption equilibrium moisture content for freshly harvested and dried red chilli were determined experimentally in a relative humidity range of 11-97% at the temperatures of 20, 30, 40 and 50 °C. Hysteresis was observed for the entire range of relative humidity and hysteresis loops decreased with increase of temperature.

The equilibrium moisture content hygroscopic-isotherms and internal surface area were investigated for five Taiwan-grown wood species by Wang and Cho (1993). The hygroscopic- isotherms of the six wood

species studied showed typical sigmoid curves. Hysteresis phenomena existed between desorption and adsorption processes. They concluded that mathematical models could be used satisfactorily to predict hygroscopic-isotherms as their analyses indicated that the calculated values are consistent with those obtained from experimental values.

The hysteresis coefficient may be defined as the ratio of equilibrium moisture content for adsorption to that at desorption for any given relative humidity. When the complete adsorption- desorption cycle was used, it ranges about 0.8 and 0.9, depending upon the wood and on the temperature. Stamm (1964) pointed out that extractives have little effect on the hysteresis ratios and that the ratios for the various isolated wood components are quite similar to those for wood. Sorption hysteresis was found to decrease with increase wood temperature and disappears at temperatures of 75°C and 100°C for European spruce in Weichert 1963. Kelsey (1957) also shows reduction in hysteresis between 25°C and 55°C for *Araucaria Klinkii* of Australia.

Effect of temperature

At all relative humidities, the equilibrium moisture content of wood is correlated with temperature in the range from 25 °C to 100 °C.

An increase in temperature reduces equilibrium moisture content. It is reported that this decrease is approximately 0.1 percent per °C increase between 25 °C and 100 °C in Sitka spruce (Koch 1985). Niemz and

Poblete (1995) reported that samples of *Pins radiata* were heated at temperatures of 100-200 °C for 24 hours or air-dried at 20 °C for 240 hours and were then conditioned at 20 °C with relative humidities of 40-95%. The equilibrium moisture content was considerably reduced as temperature increased.

Hossain and Bala (2000), working in red chilli stated that the effect of temperature on the adsorption and desorption isotherms was found significant. Also Chen *et al.* (1996) reported that there was significant moisture sorption hysteresis and that the equilibrium moisture contents of the absorption and desorption decreased with increase in temperature.

Brooker *et al.* (1992) reported that the temperature has significant effect on the equilibrium moisture content of grain and other biological products. At 70% relative humidity equilibrium moisture content for shelled corn was found to be 15.6% at 4.4 ºC and 10.3% at 60°C.

Simpson (1979) reported that sorption isotherms for wood are generally temperature-dependent. As temperature increases, the amount of vapor adsorbed at any given vapor pressure decreases.

Effect of species

Most studies on the sorption characteristics of wood have been conducted on Temperate Zone species. These showed little variation (Skaar 1972). The few studies on the tropical woods (Spalt 1957; Wangaard and Granados 1967), however, indicated some variation in the

sorption properties with species. Difference between species may be anticipated on the basis of differences in chemical composition, crystallinity of cellulose, compactness of the cell wall, and extractive content. The significance of chemical composition is evident from the work by Runkel and Liithgens who published their work in 1958 and 1959 and found substantial difference between hemicelluloses, cellulose, and lignin in hygroscopitiy (As cited in Wangaard and Granados 1967). Variations in hygroscopitiy may be expected if species are different in crystalline cellulosic content or in cell wall density.

Skaar (1972) noted that the difference among species of wood grown in the temperate regions with respect to sorption behavior is not generally very great. There are exceptions, however, particularly in woods, which have a high extractive content, such as redwood.

Koch (1985) reported that at high relative humidity, equilibrium moisture content varies slightly among southern hardwood species, but at low humidity differences appear to be minimal. Choong and Manwiller (1976) found that stem wood of 6-inch hardwood from southern pine sites did not differ significantly in equilibrium moisture content among species at 25% or 50% relative humidity. At 25% relative humidity, equilibrium moisture content averaged 5.1%, with coefficient of variation of 3.4%, which at 50%, equilibrium moisture content averaged 8.5%, with coefficient of variation of 2.8%.

Differences among species were significant, however, at 71% and 85% relative humidities.   At 71% hickory contained significantly more moisture than any other species except sweetgum. On the other hand scarlet oak contained less than any other species except shumard oak and green ash. At 85%, scarlet oak contained significantly less moisture than did white oak, wingedelm, hickory and post oak, while shumard oak contained less moisture than did hickory and post oak.

Oko,s (1976) mentioned that at 94.2 percent relative humidity, during adsorption sweetgum had highest equilibrium moisture content (23.5 percent) and that the red maple and black, scarlet, and northern red oak had the lowest equilibrium moisture content (20.6 to 20.8 percent).

Effect of chemical constituents

Change in the chemical composition of the wood may affect the equilibrium moisture content of biological material (including wood) significantly. Research on drying of grains indicated that high oil content is in equilibrium with a given set of air conditions at lower moisture content than seeds with high in starch content Brooker *et al.* (1992).

 Skaar (1972) stated that "It is well known that the sorption isotherms vary from one kind of wood to anther. This may be as a result of a number of factors such as differences among woods with respect to the proportions of the major wood constituents such as cellulose, hemicellulose, and lignin in different woods."

Wang and Cho (1993) found that "the degrees of crystallinity of cellulose and specific gravities of woods had negative effect on the equilibrium moisture content, and the holocellulose and lignin contents had positive effects. However, the effects of alcohol-benzene extractives contents on the equilibrium moisture content are uncertain"

Choong and Achmadi (1991) reported that the samples of tropical wood species were selected to undergo desorption and adsorption in the unextracted and extracted form. At high humidities, the extracted woods exhibit higher equilibrium moisture content than the unextracted woods. However, the isotherms of extracted and unextracted woods coincide at relative humidities below 70% for both desorption and adsorption. This phenomenon indicates that the hygroscopicity of wood is affected at high humidities through the extractives bulking the amorphous region in the cell wall. Also Litvay and Mckimmy (1975) noted that the extractive content exerted significant influence on the equilibrium moisture content at which the samples are equilibrated. Ladomersky (1979) reported that the equilibrium moisture content values were measured experimentally on small specimens of Oak heartwood, the same specimens extraction with water, the water soluble extractives (which accounted for 8% of Oak wood). Results showed that the extractives were less hygroscopic than the extracted wood with water and hence reduced the equilibrium moisture content of the unextracted wood relative to the extracted.

Research by Masson and Richards in 1906 on the water-sorption by cotton revealed the well-known sigmoid isotherm relating sorbed moisture to relative humidity (Wangaard and Granados 1967). Subsequent studies have contributed to current understanding of water-cellulose and water-wood sorption systems either experimentally or through the application of fundamental concepts of molecular properties and principles of physical chemistry to such systems (Spalt 1957,1958).

Choong and Achmadi (1991) reported that the mechanisms of sorption of water from the vapor phase by cellulose materials have been described in the literature. Briefly summarizing the currently held concept of sorption in wood postulates the adsorption of water by three mechanisms: Firstly as monolayer water molecules in hydrate form at polar sites in the noncrystalline regions, which predominates at low humidities; secondly as polymolecular water held in solid solution on the surface of cellulose crystallites at intermediate relative humidities; and thirdly as condensed water vapor in the void spaces of the cell wall, which is thought to occur at high relative humidities.

Control of environment

To determine adsorption and desorption equilibrium moisture content of wood, one needs to control the relative humidity and temperature. Relative humidity could be maintained either by using a saturated salt solution or an acid. A chemical mean of controlling the humidity would

be satisfactory. Saturated salt solution could be used for chemically controlling the relative humidity in a closed container (Hall 1957and Suchsland 1980).

A salt solution is more stable, less corrosive and often less expensive than the acid. A given saturated salt solution will often maintain practically the same relative humidity at different temperatures.

A solution will exert a certain vapor pressure depending upon type of the chemical, its concentration and temperature. The effect of temperature variation on the relative humidity of a given concentration of a solution depends on the chemical used. The percent relative humidity of a given concentration decreases with an increase in temperature Hall (1957). Palmer *et al.* (1987) used a method for controlling relative humidity based on temperature differentials rather than on salt solutions. They claimed that this method has the following advantages: (1) it does not exhibit the anomalous CO_2 solution effects that are found to occur with salt solutions, (2) humidity is continuously adjustable without sample removal, (3) circulation of the atmosphere results in short equilibration time.

Hall (1957) showed that saturated salt solution would be easily prepared by dissolving all of the salt into a solution, which will hold at a temperature above the one at which the tests are to be run. It is necessary that some of the solid is always present. The amount of solute

required to saturate a solution depends on the temperature for any given salt. The time required for the chemicals to come to equilibrium varies with the solution and size of the containers. Various salts were used to maintain relative humidity within closed chambers to control moisture content of grains (Hall 1957; Lange 1966; Brooker *et al.*1992) and in wood (Wangaard and Granados 1967; Litvay and Mckimmy 1975; Suchsland 1982; Zhange *et al*. 1992; Peralta1995).

Hall (1957) and Suchsland (1980) indicated that a common practice was to use an acid solution to obtain the desired relative humidities in a closed container through varying the percent of acid to obtain different relative humidity values. Sulfuric acid is usually used.

Methods of Determining the Equilibrium Moisture Content

Hall (1957) and Brooker *et al. (*1992) stated that there are two methods for the determination of the equilibrium moisture content, namely the static and dynamic method. In the static methods, the atmosphere surrounding the product comes to equilibrium with the product without mechanical agitation of the air or product. However, in the dynamic method either the atmosphere surrounding the product or the product is mechanically moved. Comparing the static and dynamic methods the dynamic is quicker but requires more instrumentation. The static method has been extensively used but several weeks may be required to reach equilibrium, which may result in moulding of the product.

Various variants of the methods for determination of the equilibrium moisture content are known. The dynamic method was used to measure the equilibrium moisture content of peanuts (Sheng 1989; Stencl *et al.* 1998; Zhang *et al.*1992). Also, the static gravimetric method was used to determine the equilibrium moisture content for adsorption and desorption of crops (Verma and Gupta 1988; Chen *et al.*1995 among others).

Teng *et al.* (1991) using a protein from soy developed a dynamic water adsorption method and the data were compared with those obtained from a static gravimetric procedure. However, both methods gave comparable results.

Peralta (1995) reported that the desiccator method was used to establish the full desorption curve, while a high-vacuum system was employed to obtain the full adsorption and four intermediate desorption curves.

Suchsland (1980) reported on a simple and rapid method for determination of sorption isotherms for wood and processed wood materials. Small specimen (0.2 g) are conditioned in small desiccators (75-mm diameter) over saturated salt solution. Specimens remain in the minidesiccators while being weighed on an analytical balance; the various point of the sorption isotherm can be determinate simultaneously.

Lee *et al.* (1998) described a method for estimating equilibrium moisture content at high vapor pressures and high temperatures above 100 °C. Equilibrium moisture content was investigated under saturated vapor pressures above 1 atm. Moisture content was calculated from a quartz spring elongation by vapor sorption, which showed good agreement with Moisture content determined by the oven-dried method.

Equilibrium Moisture Content Model

Several theoretical and empirical models have been proposed for calculating the moisture equilibria. An add discussion on the theoretical equilibrium moisture content models is given by Brooker *et al.* (1992). These models are based on capillary condensation (Kelvin model), kinetic adsorption {Langmuir and Brunauer, Emmett and Teller (BET)} or field-strength potential (Harkins-Jura). Brooker *et al.* (1992) noted that, among the theoretical equilibrium moisture content models, only the GAB model is capable of predicting accurately the moisture equilibrium isotherms of grains over full temperature and relative humidity ranges encountered in practical grain drying situations. However, the lack of knowledge of the product constants for grains in the GAB equation forced engineers to employ purely empirical equations (Henderson or Chung) in dryer design calculations (Brooker *et al.* 1992). Correa *et al.* (1999) reported that the desorption tests of wood chips with an intial moisture content of approximately 45% (dry basis) were carried

out in an air conditioning unit (Aininco-Air) to control the temperature (20, 35, 50 and 65 $^{\circ}$C) and relative humidity (15, 30, 45, 60, 75 and 90%). The sample remained in chamber until its moisture reached hygroscopic equilibrium. Among the various equations fitted to the moisture data, the Chung-pfost and Guggenheim-Anderson-de Boer equations well fitted the variation in the wood equilibrium moisture in relation to the air temperature and relative humidity.

Working on samples from *Lotus corniculatus* stems Stencl *et al.* (1998) evaluated the ability equilibrium moisture content / equilibrium relative humidity equations to fit experimental data. They used the dynamic method with continuous registration of sample weight changes was used as an experimental procedure. Air temperatures of 30, 35, 40, 45 and 50 $^{\circ}$C and relative humidities of 40, 50, 60, 70, 80, 90 and 100% were used to obtain equilibrium moisture content data of the material tested.

The experimental exponential equation was a good model for desorption of sorption behavior stems of *lotus corniculatus* under test conditions both for adsorption and desorption. Zang *et. al.* (1992) adopted the dynamic method to measure equilibrium moisture content of persimmon in a sealed container above a saturated salt solution at different temperatures. They created airflow by means of a miniature flow fan in order to determine the sorption and desorption curves at 20- 30 $^{\circ}$C. A mathematical model of the persimmon equilibrium moisture content was

developed. Working on *Litchi,* Chen *et. al.* (1995) determined the equilibrium moisture content for adsorption and desorption in a temperature range of 10-40 $^{\circ}$C and a full range of relative humidity. Regression analysis indicated that Henderson equation could be used to describe the equilibrium moisture content curves for both adsorption and desorption. Yang and Niu (1993) investigated the equilibrium moisture content for adsorption and desorption of two varieties of jujubes (*Ziziphus sativa*) at 10-50 $^{\circ}$C and a range of relative humidity. Various equations were compared for their ability to fit the experimental results and a model was developed to describe the adsorption and desorption isotherms of jujube.

Oliver and Chhinnan (1980) reported that the study data was obtained to plot sorption and desorption isotherms for Stuart type pecan kernels and shell at temperatures 10, 20, 30 and 40 $^{\circ}$C. Seven different equations were evaluated to fit the data. Henderson equation was found to be the most suitable to predict the equilibrium moisture content for pecan components.

CHAPTER III

MATERIALS AND METHODS

MATERIALS

Wood Material

Six hardwood species of various densities were used for this study. The high-density species were *Acacia nilotica* var *tomentosa* (L.) Willd. ex-Del.*, Acacia senegal* (L.) Willd. and *Anogeissus leiocarpus*(DC) Guill and Perr. The low-density species were *Boswellia papyrifera* (Del.) Hochst, *Calotropis procera* (Ait) Ait. F. and *Ailanthus excellsa* Roxb. Six trees from each species were felled and a log of a meter length was taken from the main stem starting from the base of the log. Table 3.1 shows the collection site for the different species.

Table 3.1. Collection sites of the study material

Scientific name	Local name	Collection site
Calotropis procera	Usher	High way (Kosti-Elobied)
Acacia senegal	Hashab	Domokia forest
Acacia nilotica var tomentosa	Sunt	Elain Forest Reserve
Anogeissus leocarpus	Sahab	Umm Abdalla and Rashad
Ailanthus excellsa	Ailanthus	Umm Abdalla and Rashad
Boswellia papyrifera	Gafal	Umm Abdalla Natural Forest Reserve

Log of the different tree species was cut into small pieces of 1.5x3.5x50 cm, which were kept in polythene bags and later stored in a cold chamber to keep moisture content at green condition (Figure 3.1).

Other requirements

The following equipment and chemicals were used in the experiment:

(1)   An oven for the determination of equilibrium moisture content, extractives content and density of wood.

(2)   A sensitive balance of Meller make with an accuracy of ±0.0 gram

(3)   Thermometers to measure the temperature.

(4)   Desiccators in which the samples of wood were tested for equilibrium moisture content determination.

(5)   A glass rod to stir the saturated salt solutions.

(6)   Delta T-logger DL2e type and copper-constantan thermocouples commercially marketed by delta-T Devices limited-England were employed to record salt solution temperature and both dry and wet blubs temperature of air inside the desiccator.

(7)   Fan made was directed to the thermocouples assigned to record both wet and dry temperatures, in order to create the required air around the   above thermocouples.

(8)   Polythene bags are employed to prevent losses in moisture content of   the wood.

(9)   Aluminum foil is used to wrap the samples.

METHODS

Determination of the Sorption Isotherms

The sorption isotherms were determined at two temperatures for each species. The sorption isotherm shows the equilibrium moisture content of wood at a given temperature and different values of relative humidity. Various relative humidities were maintained closed desiccators using saturated salt solutions or sulphuric acid at different concentrations.

Preparation of the saturated salt solution

Placing the required number of desiccators inside the oven, each desiccator containing 100 mls of distilled water, did the preparation of the saturated salt solution of each isotherm. After a period of 24 hours; the temperature of the distilled water in each desiccator was measured to make sure that the required temperature was attained. While adding the salt, the solution was stirred using a glass rod. Addition of the salt was continued until there was only a small excess mount remaining un-dissolved. Then the desiccators were left for a period of 24 hours inside the oven to make sure that the prepared solution was saturated. The amounts of the salts needed to saturate the solvent (100 ml of distilled water) are shown in Table 3.2.

To measure relative humidity inside the desiccator, the thermocouples were concerted to a delta T-logger. A small fan (9-cm) was connected to delta t- logger to ensure ventilation around the thermocouples. Tow

thermocouples were assigned to record the wet and dry blub temperatures of the air inside the desiccator.

The different salts solutions used in this study, together with their corresponding relative humidities at 60°C are given in Table 3.3 and at 90 °C are given in Table 3.4.

Table 3.2. Weight of salt required for saturating 100 ml of distilled water.

Chemical	Weight / concentration	
	at 60 °C	at 90 °C
KSo_4	22	23.10
KCl	50	.
NaCl	37	40
$NaNO_3$	115	151
NaBr	140	100
$MgCl_2$	59.4	63.6
H_2SO_4	60	.
H_2SO_4	80	.
H_2SO_4	90	.
KNO_3	.	140
LiCl	.	126.2

Source: Lange, N.A. (1966). Handbook of chemistry. McGraw-Hill Book Co., New York, Francisco, Toronto, London, and Sydney.

Table 3.3 Relative humidities at 60 °C maintained by the different salt
solution used in this study.

Salt chemical formula.	Relative humidity %
$H_2 So_4$	7
$H_2 So_4$	15
$H_2 So_4$	20.5
$MgCl_2$	30
NaBr	50
$NaNo_3$	67
NaCl	75
KCl	80.5
$K_2 So_4$	95

Source: Hall, C.W. (1957). Drying farm Crops. AVI Publishing Inc,
        Westport Connecticut.

Table 3.4 Relative humidities at 90 °C maintained by the different salt solution used in this study.

Salt chemical formula	Relative humidity %
LiCl	11
$MgCl_2$	28
NaBr	51
$NaNo_3$	65
NaCl	75
KNo_3	80
$K_2 So_4$	90

Source: Hall, C.W. (1957). Drying farm Crops. AVI Publishing Inc, Westport Connecticut.

Determination of the Desorption Isotherm

For the determination of the desorption isotherms at 60°C, it is necessary to provided a number of relative humidities conditions at constant temperature to which samples are exposed until they reached their equilibrium moisture content.

For each species, six samples were randomly selected for the determination of the equilibrium moisture content. Samples were placed in the desiccator containing the saturated salt solution of the potassium sulphate (K_2SO_4) and they were then kept inside the oven at 60°C. The exerted relative humidity of

salt found to be maintained at 95 %. Then the samples were weighed until constant weight was obtained or at least there was a difference of ±0.01 gram between two successive readings. When samples reached constant weight, they were transferred to another desiccator containing saturated salt solution of potassium chloride (RH 80.5 %) and the desiccator was placed inside the oven at the same temperature, until constant weight of the samples was obtained. The same procedure was applied using the other salts (Table 3.2). Data obtained from the experiment were used to draw the full desorption curves for the six species.

Determination of the Adsorption Isotherm

After desorption curve was obtained the tested samples were transferred to an oven and all samples were left to be dried in to an oven at temperature of 103°C ±2. Then they were weighed and the process of drying was continued until constant weight was obtained. Then the samples were placed inside the desiccator containing saturated salt solution of the lithium chloride (RH 11.2%), each desiccator was placed inside the oven at 60°C. The weight was taken every 24 hours until the constant weight was obtained or at least there was a difference of ±0.01 gram between two successive weights. When samples reached constant weight in the desiccator they were transferred to another desiccator containing saturated salt solution of the calcium chloride

(RH 32.8%) and each desiccator was replaced inside the oven until the constant weight was obtained. Then samples were transferred to another desiccator containing saturated salt solution. The same procedure was applied for the other salts, then the adsorption curve was drawn by using the obtained data. The same procedure was applied at 90°C to obtain the full cycle desorption and adsorption.

Determination of the Wood Density

Density of homogeneous material is defined as its mass per unit volume

Density = Mass
                   Volume

The simple method of determining the density of a piece of wood is to weigh it and then determine its volume. Because the specimens were cut into small blocks of irregular shape, it was necessary to determine their volume by using a displacement technique (Figure 3.2.). A beaker of water was placed on balance, then the samples, suspended by a needle clamped in a stand, was then gently lowered into the beaker and completely immersed in the water without touching the sides of the beaker or any of the water running over the top of beaker. The volume of the samples is equal to the volume of displaced water (cm^3) which, in turn, is numerically equal to the weight of displaced water in the beaker. The weight of displaced water was determined as the difference in the balance reading before and after immersion of the

samples. Then all samples were placed in the oven (103 ±2) for three days or until the weight was constant. This constant weight was considered the oven-dry weight.

The wood density values were calculated employing the following equation

Basic wood density $= \dfrac{\text{Oven-dry weight}}{\text{Green volume}}$

Determination of Extractive Content

The wood of each of the tree species was subjected to extraction, using hot water (Figure 3.3). The extraction method was carried out according to ASTM (1981). Two grams of each sample of the raw material under study were subjected to extraction for three hours using 100 mls of distilled water placed in Erlenmeyer flask, which was attached to the boiling water bath. The contents of flask were filtered and dried to a constant weight at 100 - 105 ºC then weighted. The results were used to determine the hot water extractive content as follows

$$\text{Ex} = \dfrac{W_1 - W_2}{W_1}$$

Where W_1 = weight of moisture - free wood prior to test.

W_2 = weight of dried sample after extraction.

Determination of Desorption and Adsorption Equilibrium Moisture Content Isotherms

Three samples from each species were selected to undergo desorption and adsorption in the unextracted and extracted forms. The samples were divided into two groups, each consisting of three replications untreated (unextracted condition) and treated (extracted condition). Samples of group B were subjected to hot water extraction. The extraction was continued until the solution surrounding the samples in the beaker was visibly free of color from dissolved extractives. All species in the extracted or unextracted condition, with three replications for each, were tested simultaneously in the desiccator. The samples were exposed to seven different relative humidities ranging from approximately 20.5-95 percent, first in desorption and subsequently in adsorption. Data obtained from the experiment were used to draw the full cycle desorption and adsorption for the three species.

Statistical Analysis

Both linear and third-order polynomial regression analysis Neter *et al.* (1983) was used to describe the trend of relation between equilibrium moisture content and relative humidity. Also the simple linear regression of desorption and adsorption equilibrium moisture content on relative humidity was conducted on the pooled data od 60 and 90 $^\circ$C. For the data of each temperature separately using Statistical Analysis Systems (SAS Institute Inc,

1989). Analysis of variance (Petersen, 1985) was conducted to investigate the

significance of different of species and extractives wood.

Chapter IV

RESULTS AND DISCUSSION

Three of the so many factors affecting the equilibrium moisture content of the six studied species were investigated. These factors are relative humidity, species, temperature and extraction. The collected data of the four isotherms at temperatures of 60 $^{\circ}$C and 90 $^{\circ}$C for desorption and adsorption equilibrium was presented on plots for each species. The effects of each of the relative humidity and temperature were investigated by interpretation of the shape of the four isotherms and by statistical analysis using regression equations. The effect of species and extractives on the equilibrium moisture content was investigated by analysis of variance and comparing desorption and adsorption equilibrium moisture content values of one species with those of the other.

To characterize the raw material, wood density and extractives content were determined for each of the six species. Tables 4.1 show the minimal, means with standard deviation and maximal for wood density of the six species.

Relationship between equilibrium moisture content and relative humidity at 60 ˚C

Desorption

The results presented in Figures 4.1– 4.6 show the relationship between equilibrium moisture content and relative humidity at 60 ˚C for Sunt, Hashab, Sahab, Gafal, Ailanthus, and Ushar respectively.

The shape of the isotherms for all plots indicates that there is a direct relationship between the equilibrium moisture content and relative humidity. In the desorption curve, the equilibrium moisture content decreases as the relative humidity decreases and in the adsorption isotherms, as the relative humidity increases the equilibrium moisture content increases. These sorption isotherms can be well described by the sigmoid curve. These results are in agreement with the findings of Sheng (1989), Wang and Cho (1993), Chen et al. (1996) and Hossain and Bala (2000).

Depending on the rate of change in the equilibrium moisture content with the relative humidity, each of the curves can be divided into four sections, namely, between relative humidities 0 to 15, 15 to 30, 30 to 75 and 75 to 95%. The average values of the rate of change in desorption equilibrium moisture content per unit change in relative humidity of the six species are given in Table 4.2.

For Sunt, the rate of change in desorption equilibrium moisture content in the first, second, third and fourth relative humidity ranges were, respectively, 0.0677, 0.3581, 0.1477 and 0.4450 for each 1% change in relative humidity. For Hashab, it was respectively, 0.0677, 0.3266, 0.1580 and 0.4327, while For Sahab, it was respectively, 0.0573, 0.3133, 0.1338 and 0.3850 1% for every change in relative humidity.

For Gafal, Ailanthus and Ushar the rate of change in desorption equilibrium moisture content was respectively, 0.0596, 0.0383 and 0 in the first range; and it increased to, 0.3333, 0.3343 and 0.3333 respectively, in the second range. The range rate of change for the three species were, respectively, 0.1466, 0.1550 and 0.1410 in the third range and 0.5637, 0.5637 and 0.6950 for each unit change in relative humidity in the fourth section.

Adsorption

Average values of the rate of change in adsorption equilibrium moisture content in the four ranges are given in Table 4.3.

The rate of change in adsorption equilibrium moisture content for Sunt in the first range was 0.0133 for each 1% change in the relative humidity. In the second range the rate increased to 0.2866, adsorbed to 0.1188 in the third section and then increased again to 0.2950 in the fourth range. The rate of change in adsorption equilibrium moisture content were, respectively, 0.0133,

0.2808, 0.1209 and 0.3620, for Hashab and 0.0251, 0.2346, 0.1044 and 0.2588 in Sahab per unit increase in relative humidity in the first, second, third and fourth ranges.

For Gafal, the rate of change in adsorption equilibrium moisture content in the first, second, third and fourth ranges were respectively, 0.0178, 0.2666, 0.1244 and 0.4313 and it was 0.0266, 0.2797, 0.1355 and 0.4108 for Ailanthus and 0, 0.2666, 0.1198 and 0.4355 for Ushar.

The above results indicate that desorption and adsorption isotherms (of the six species) followed similar trends.   The relationship between equilibrium moisture content and relative humidity can reasonably be divided into four segments.   At the lower range of relative humidity (0- 30%), equilibrium moisture content increased gradually with increasing relative humidity, then it showed a higher rate of change followed by a third segment of low rate of change. The fourth segment of the curve was characterized by the highest rate of change in equilibrium moisture content.

These results indicate that the species with lower wood density (Ailanthus, Gafal and Ushar) had a lower rate of change in desorption and adsorption equilibrium moisture content in the first section than the species with high wood density. In the middle section (second and third) the rate of change in

equilibrium moisture content appears to be similar in both groups of species.

However, in the fourth section the species

with lower wood density had a higher rate of change in desorption equilibrium moisture content than the species with high wood density.

The differences between the desorption and adsorption isotherms at low relative humidity (0-30%) were minimal and they increased with increasing relative humidity values up to relative humidity 80%.

Desorption and adsorption curves for Ailanthus and Ushar did not differ between relative humidities 0-15% and the differences started to appear then after.

Relationship between equilibrium moisture content and relative humidity at 90 $^\circ$C

Desorption

The results presented in Figures 4.7-4.12 show the relationship between equilibrium moisture content and relative humidity at 90 $^\circ$C for Sunt, Hashab, Sahab, Gafal, Ailanthus and Ushar, respectively. The shape of the isotherms for all plots indicates that it is similar to the results at temperature 60 $^\circ$C. There is a direct relationship between equilibrium moisture content and relative humidity; as the relative humidity increases the equilibrium moisture content increases and vice versa. These sorption isotherms can also be well described by the sigmoid curve. However, depending on the rate of change in equilibrium moisture content with relative humidity, the curve can be divided into three sections, namely, between relative humidities 0 to 11, 11 to 80 and

80 to 90% of change in desorption. The average values of the rate of change of desorption equilibrium moisture content in these sections are given in Table 4.4

For Sunt, the rate of change in desorption equilibrium moisture content in the first, second and third ranges were 0.1910, 0.1205 and 1.096 respectively, for each 1% change in relative humidity.

The rate of decrease in the equilibrium moisture content in Hashab was respectively, 0.1644, 0.1100 and 1.0192; and 0.1450, 0.0880 and 0.8582 in Sahab. The rate of decrease in desorption equilibrium moisture content in the first, second and third sections was, respectively, 0.110, 0.1210 and 1.4367 in Gafal, 0.1557, 0.1422 and 1.390 in Ailanthus and 0.1727, 0.15459 and 1.6368 in Ushar.

Adsorption

The average values of the rate change in adsorption equilibrium moisture content per unit change in relative humidity in the three sections are given in Table 4.5.

The rates of change in adsorption equilibrium moisture content for Sunt in the first second and third ranges were respectively, 0.1364, 0.0826 and 1.383 for each 1% change in relative humidity.

The rate of increase in adsorption equilibrium moisture content was, respectively, 0.1272, 0.0696 and 1.3049 in Hashab and 0.1111, 0.0609

and 0.9687 in Sahab. The rate of increase in equilibrium moisture content in the first, second and third sections was, respectively,

0.0818, 0.0609 and 1.5048 in Gafal, 0.0818, 0.0928 and 2.7378 in Ailanthus and 0.1727, 0.0681 and 1.8756 in Ushar.

The relationship between the equilibrium moisture content and the relative humidity at temperature 90 $^{\circ}$C exhibited typical sigmoid shape (Figures 4.7-4.12). The shape of the isotherms for desorption and adsorption indicates that there is a direct relationship between equilibrium moisture content and relative humidity, as the relative humidity increases the equilibrium moisture content increases.

The above results indicate that desorption and adsorption isotherms (of the six species) followed similar trends.   The relationship between equilibrium moisture content and relative humidity can be divided into three segments. At the lower range of relative humidity (0-11%) equilibrium moisture content increased rapidly with increasing relative humidity, then it showed a lower rate of change up to relative humidity 80%.   The third segment of the curve was characterized by the highest rate of change in equilibrium moisture content. The differences between desorption and adsorption isotherms at low relative humidity (0-11%) were minimal and they increased with increasing relative humidity values up to relative humidity 80% and got closer thereafter.

Desorption and adsorption curves for Gafal and Ushar did not differ between relative humidities 0-11% and the differences started to appear after that.

Hysteresis loops

Equilibrium moisture content at a given relative humidity depends on whether the level of moisture in the wood has decreased (desorption) or increased (adsorption) to reach equilibrium.

Desorption isotherm curve in the six studied species is invariably higher than the adsorption isotherm curve and this is known as sorption hysteresis. This phenomenon has been explained in terms of the loss and gain of hydroxyl groups. In the original green condition, the available polar hydroxyl groups in cell wall polymers are almost entirely satisfied by bound water. In dry wood, which has lost its bound water, however, shrinkage brings the polar hydroxyl groups close enough together to satisfy each other; this results in diminished adsorption when re-wetted (Koch 1985; Haygreen and Bowyer 1989).

Results of this study (Figures 4.1-4.6) show that at temperature 60 $^{\circ}$C the hysteresis loop is open at the upper end of the curve (at high relative humidities). However at temperature 90 $^{\circ}$C, three species (*Acacia nilotica, Acacia senegal* and *Ailanthus excelsa*) exhibited a closed hysteresis loop while in the other three species the values of desorption and adsorption equilibrium moisture content were very close to each other at the upper end of the curves.

Peralta and Bangi (1998) also observed open-ended hysteresis loops in *Porous media*, Wang and Cho (1993) and Avramidis (1989) in sixteen tropical wood species and Sheng (1989) in *Spanish Peanuts*.

This is contrary to the closed hysteresis loop commonly described in the literature (Koch 1985; Skaar 1972). Wangaard and Granados (1967) who indicated that not all researchers have been able to observe that the hysteresis loop is closed at the upper end.

Browning in 1976 (as cited in by Koch 1985) stated that a closed hysteresis loop is obtained only when desorption data are observed after adsorption data. The phenomena of open ends of the hysteresis loop remain unexplained. The finding of the current study for sorption at 90 $^{\circ}$C do not support this statement.

Modeling

In practice it is usually desired to employ as simple a regression model as possible, which in the case of polynomial regression means a lower-order model. Simple linear regression of desorption and adsorption equilibrium moisture content on relative humidity was conducted on the data of 60 and 90 $^{\circ}$C separately. This will give simple regression equation that can be used in the range of temperature observations (60- 90 $^{\circ}$C).

The results for the six species are shown in Table 4.6 for desorption and adsorption at 60 $^{\circ}$C. In general, the direct relationships between desorption

equilibrium moisture content and relative humidity can be satisfactorily represented by linear regression equations. This is evident from the highly significant the regression coefficients (P<0.0001) and the high coefficients of determination (R^2= 0.946 to 0.860). For Sunt, Hashab, Sahab, Gafal, Ailanthus and Ushar, the regression equations show that the average change in equilibrium moisture content for each one-unit change in relative humidity was 0.216, 0.218, 0.192, 0.277, 0.235 and 0.237, respectively. These results indicate that the high-density wood species showed a relatively lower average rate of change in equilibrium moisture content per 1% relative humidity than the low-density wood species.

Linear regression equations of the adsorption equilibrium moisture content on relative humidity for the six species are shown in Table 4.6.

The result show that the regression coefficients are significantly different from zero at a probability levels equal to 0.0001. The regression equations could explain between (R^2 0.940 to 0.855) of the variation in adsorption equilibrium moisture content. For Sunt, Hashab, Sahab, Gafal, Ailanthus and Ushar, the regression equations show that equilibrium moisture content is expected to change for each one unit change in the relative humidity by 0.166, 0.174, 0.142, 0.182, 0.189 and

0.174, respectively. Generally, the species with low wood density have higher average rate of change in adsorption equilibrium moisture content than the high wood density. However, these rates of change in adsorption are clearly lower than those of desorption equilibrium moisture content.

Results for the six species are shown in Tables 4.7 for 90 $^{\circ}$C. In general, the direct relationships between desorption equilibrium moisture content and relative humidity can be satisfactorily represented by linear regression equations. This is evident from the low P- value (P= 0.006 to 0.013) and the relatively high coefficients of determination (R^2= 0.738 to 0.642). For Sunt, Hashab, Sahab, Gafal, Ailanthus and Ushar, the regression equations show that the average change in equilibrium moisture content for each one-unit change in relative humidity was 0.172, 0.155, 0.129, 0.182, 0.197 and 0.221, respectively. These results indicate that the high-density wood species showed a relatively lower average rate of change in equilibrium moisture content per 1% relative humidity than the low-density wood species.

Linear regression equations of the adsorption equilibrium moisture content on relative humidity for the six species are shown in Table 7.6. The results show that the direct relationship between adsorption equilibrium moisture content on relative humidity can be satisfactorily represented by linear regression. This is evident from the low P-values

(P= 0.005 to 0.070) and the relatively high (R^2 0.641 to 0.448) of the variation in adsorption equilibrium moisture content. For Sunt, Hashab, Sahab, Gafal, Ailanthus and Ushar, the regression equations show that equilibrium moisture content is expected to change for each one unit change in the relative humidity by 0.150, 0.134, 0.108, 0.135, 0.196 and 0.163, respectively.

Effect of temperature

Results of the linear regression analysis of desorption equilibrium moisture content on the temperature (Table 4.8) indicate negative relationship between them. This is evident from the high levels of probability (P= 0.610 to 0.917) and low coefficients of determination (R^2 = 0.001 to 0.009).

Results of the linear regression analysis of adsorption equilibrium moisture content on the temperature (Table 4.9) indicate negative relationship between them. The results show that temperature exhibited no significant effect on equilibrium moisture content. This is evident from the high level of probability (P= 0.703 to 0.967) and low coefficients of determination (R^2 = 0.000 to 0.009).

The non-significance of the negative relationship between equilibrium moisture content and temperature might be due to the fact that the range of temperature studied is relatively narrow (60 - 90 $^{\circ}$C) and the number of observations is too small.　　Perhaps　it　is　too　much　to　expect　these

equations to accurately estimate equilibrium moisture content between even 60 and 90 $^{\circ}$C. Hence, significance differences in equilibrium moisture content between temperature, if any, might only be indicated when a larger range of temperature is investigated. However, many researchers indicated that the effect of temperature on equilibrium moisture content is of a lower magnitude in comparison to that of relative humidity (Chen, *et al.* 1995, Skaar 1972 and Siau 1971).

The results of the linear regression analysis of desorption and adsorption equilibrium moisture content on the relative humidity and temperature (Table 4.8 and Table 4.9) indicate that even when relative humidity is in the model, temperature does not explain a significant part of the variation in equilibrium moisture content.

Regression analysis was used to describe the statistical relationship between equilibrium moisture content and relative humidity. It describes the general tendency by which the two variables are related. The data strongly suggest that the relationship between equilibrium moisture content and relative humidity could be modeled using a curvilinear, polynomial cubic trend. The results are presented in figures 4.13 - 4.18 for desorption and 4.19 – 4.24 for adsorption, which show average values of the experimental data and the best fit trend lines. These results show that the trend of equilibrium moisture

content and relative humidity relationship could be well explained by the third-order polynomial equation; all trend lines gave highly significant relationships (P= 0.001) with coefficient of determination (R^2) ranging from 0.978 to 0.989. This means these equations were able to explain more than 97% of the variation of equilibrium moisture content.

The polynomial regression equations presented in this study are of great practical importance. One practical use of these equations is their excellent ability to correlate and interpolate sorption data at least for the studied species. Equilibrium moisture content can be calculated with great precision over the entire range of the studied relative humidity.

For example, at relative humidity 60%, the expected desorption equilibrium moisture content for Sunt will equal 9.55%when using the polynomial equation. At the same relative humidity the values will be, 9.66% for Hashab, 9.15% for Sahab, 9.09% for Gafal; 8.30% for Ailanthus and 8.00% for Ushar.

At the same relative humidity (60%) the expected adsorption equilibrium moisture content for Sunt will equal 6.70% when using the polynomial equation. For the other species, the respective values will be, 6.80% for Hashab, 5.41% for Sahab, 6.74 % for Gafal, 7.31% for Ailanthus 5.20% for Ushar, these results can further be used to estimate the average hysteresis at a given relative humidity. If we continue with the same example, the average

hysteresis at 60% relative humidity can be shown to equal 2.85, 2.86, 3.74, 2.35, 099 and 2.80% for Sunt, Hashab, Sahab,

Gafal, Ailanthus and Ushar respectively. Simpson (1979) showed that, depending on the shape, sorption curves could be divided into five types. Accordingly, the sorption curves found in this study at temperature 60 °C can be classified as type 2. This type of curves is characteristic of sorption where more than one layer of vapor is formed on the solid and where the forces of attraction between the vapor and solid are large.

Results of the regression analysis at temperature 90 °C are presented in Figures 4.25 - 4.30 for desorption and 4.31 - 4.36 for adsorption in these figures, the best-fit, trend lines for the relationship between the equilibrium moisture content and have been plotted relative humidity.

The trend of equilibrium moisture content and relative humidity relationship could also be explained by the third-order polynomial equation; all trend lines gave highly significant relationships (P> 0.001) with coefficients of determination (R^2) ranging from 0.898 to 0.972. However, the values and scattering of points suggest that the amount of variation in equilibrium moisture content, which is explained by relative humidity at 90 °C is less than at 60 °C.

In general, the third polynomial gave the best-fit trend lines because of the higher R^2 value obtained in comparison with other equations.

The linear and polynomial regression equations presented in this study are of

practical importance. One practical use of these equations is their

excellent ability to correlate and interpolate sorption data at least for the studied species.

Following the classification of Simpson (1979) the type of sorption curves found in this study at temperature 90 °C can be classified as type 2. This type of curves is characteristic of sorption where more than one layer of vapor is formed on the solid and where the forces of attraction between the vapor and solid are large.

Differences between species in equilibrium moisture content at 60°C Desorption

For each species replicate determination of equilibrium moisture content at nine levels of relative humidity were carried out on both desorption and adsorption isotherms. Results of the analysis of variance revealed significant differences between species at all levels of relative humidity except at 30%. The mean values of the six species and the results of Duncan's Multiple Range Test are given in Table 4.10.

At relative humidity 95%, Ushar had the highest equilibrium moisture content value and there were no significant differences between it and Ailanthus and Gafal. Ushar was significantly different from the other three species. However, there were no significant differences between Gafal, Hashab and Sunt. Sahab had the lowest equilibrium moisture content values.

At relative humidity 80.5%, Ailanthus and Hashab had the highest equilibrium moisture content values; Gafal and Sunt followed in rank and they were not significantly different from Ushar. Sahab had significantly the lowest equilibrium moisture content value.

At relative humidity 75%, Ailanthus, Hashab and Sunt had the highest equilibrium moisture content values and they were followed by Gafal, which was not significantly different from Sahab and Ushar. At relative humidities 67% and 50%, Sunt had the highest equilibrium moisture content value and Ailanthus, Gafal and Hashab followed. Ushar and Sahab had the lowest equilibrium moisture content value.

At relative humidity 30%, there were no significant differences between all species. At relative humidities 20.5% and 15%, Ailanthus, Gafal, Sunt, Hashab and Sahab had the highest equilibrium moisture content values and they were not significantly different from each other. Ushar had significantly the lowest equilibrium moisture content value. At relative humidity 7%, Sunt, Hashab and Sahab had significantly higher equilibrium moisture content values than Ailanthus, Gafal and Ushar.

The above results indicate that at the highest relative humidity (95%) the species with low wood density had higher desorption equilibrium moisture content than the species with high wood density

Adsorption

Species means of the adsorption equilibrium moisture content for the various relative humidities and results of the Duncan's Multiple Range Test are presented in Table 4.11.

At relative humidity 95%, Ailanthus and Gafal had the highest equilibrium moisture content values and they were significantly different from Ushar and Hashab. Sahab had a significantly lower equilibrium moisture content value than all other species.

These results indicate that as relative humidity approaches saturation point the species with low wood density had higher adsorption equilibrium moisture content than the species with high wood density.

At relative humidities 80.5% and 75%, Ailanthus had the highest equilibrium moisture content value and it was not significantly different from Gafal, Hashab and Sunt, which were not significantly different from Ushar. Sahab had significantly lower equilibrium moisture content value than all other species. At relative humidity 67%, the highest values were recorded for Ailanthus, Gafal, Hashab and Sunt with no significant differences between them. Ushar and Sahab had significantly lower equilibrium moisture content values than other species but they were not significantly different from each other.

From relative humidities 50% to 7%, it can be noted that there were not

significant differences between the species. Five of studied species did

not adsorb any moisture up to relative humidity 7% and the sixth the species (*Calotrapus procera*) did not adsorb moisture up to relative humidity 15%.

Figures 4.37-4.38 show that at higher relative humidities the variation between the means of species was greater than at lower relative humidities. The differences were remarkably at relative humidity 95%. **Differences between species in equilibrium moisture content at 90 $^\circ$C**

Desorption

The results of the analysis of variance showed significant differences between species in desorption equilibrium moisture content at 90 $^\circ$C. The values of the equilibrium moisture content for the six species studied and the results of Duncan's Multiple Range Test are given in Table 4.12. At relative humidity 90 %, Ushar had the highest equilibrium moisture content value and it was not significantly different from Ailanthus. Hashab and Sahab had the lowest equilibrium moisture content values. At relative humidity 80 %, Ushar had the highest equilibrium moisture content value and it was followed by Ailanthus; they were significantly different from each other and from all other species. Sahab had the lowest equilibrium moisture content value and was significantly different from all other species.

At relative humidities 75% and 65%, Sunt and Ushar had the highest equilibrium moisture content values and it was not significantly different

from Ushar, which was not significantly different from Ailanthus and Hashab. At relative humidities 51% and 28%, Ushar, Sunt and Hashab had the highest equilibrium moisture content values and they were followed by Ailanthus, which was not significantly different from Hashab. Gafal and Sahab had the lowest equilibrium moisture content values. At relative humidity 11%, Ushar, Ailanthus, Sunt and Hashab had the highest equilibrium moisture content values and they were significantly different from Gafal, which had the lowest value. The above results revealed that at the highest relative humidity values (90% and 80%) the lower wood density species ranked higher than the species with the higher wood density.

Generally speaking, from relative humidity 75% to 11%, Ushar and Sunt consistently had the highest equilibrium moisture content values and they were followed by Ailanthus and Hashab. Sahab and Gafal consistently had the lowest equilibrium moisture content.

Adsorption

There were significant differences (P= 0.0001) between species in adsorption equilibrium moisture content at all relative humidities.

Means of the species and the results of the Duncan's Multiple Range Test are presented in Table 4.13.

At relative humidity 90%, Ailanthus had the highest equilibrium moisture content value followed by Ushar, Sunt, Gafal and Hashab with significant difference. Sahab had significantly the lowest value.

At relative humidity 80%, Ailanthus, Sunt, Ushar and Hashab had the highest equilibrium moisture content values and they were significantly different only from Gafal and Sahab, which were associated with the lowest values. At relative humidities 75% and 65%, Sunt had the highest equilibrium moisture content value compared to all other species except Hashab, which had the same rank at relative humidity 65%.

At relative humidities 51% and 28%, Sunt and Hashab ranked high in adsorption equilibrium moisture content and were not significantly different from each other; they were followed by Ailanthus and Sahab. Gafal, Ushar and Sahab had the lowest values, which were significantly different from all other species. At relative humidity 11%, Ushar and Sunt had the highest values, followed by Hashab and Sahab. Ailanthus and Gafal had significantly lower values that all other species.

Similar to the behavior of desorption and adsorption at 60 $^{\circ}$C and desorption at 90 $^{\circ}$C, the adsorption equilibrium moisture content at 90 $^{\circ}$C and 90% relative humidity showed relatively higher values in the species with low wood density than in the one with high wood density.

From relative humidity 80% to 28%, Sunt consistently had the highest

equilibrium moisture content and it was followed either by Ailanthus or

Hashab. At this range Ushar and Gafal were associated with the lowest rank.

The results presented for the data collected at 60 and 90 °C give evidence for significant variations between species in both desorption and adsorption equilibrium moisture content. However this variation and ranking of species depends on the level of relative humidity.

In spite of the overlap of the grouping of the mean separation test, it can be seen that there is a difference between the species with low wood density and those with high wood density. Differences between species may be anticipated on the basis of differences in chemical composition, crystallinity of cellulose, compactness of the cell wall and extractive content. The significance of composition is evident from the work of Skaar and Kelsey (1958, 1959) who found substantial differences between hemicelluloses, cellulose, and lignin in hygroscopicity. Such differences coupled with variations in crystalline cellulosic content or in cell wall density among species are expected to result in variations in hygroscopicity.

At higher relative humidities the equilibrium moisture content varied remarkably among species, but at lower relative humidities differences appear to be minimal (Figures 4.39 - 4.40). This strongly goes in line with the findings of Choong and Manwiller in 1976 (Koch 1985) who found that differences between species are greater at higher levels than at lower levels of

relative humidity. The differences between species were greater at temperature 90 $^\circ$C than at 60 $^\circ$C (Figures 4.37 – 4.38).

Due to the great variation between species especially at high relative humidities it will not be wise to develop one generalized model for the six species. This is because such variation will reduce the precision with which the generalized model describes the isotherms.

EFFECT OF EXTRACTIVES ON THE EQUILIBRIUM MOISTURE CONTENT

Extractive contents of the six studied species are given in Table 4.14. The values ranged between 19.75% (*Acacia senegal*) to 6.57% (*Ailanthus excelsa*). These figures are within the range found by Mohammed (1999).

For each of the species, replicate determinations of the equilibrium moisture content at seven levels of relative humidity were made on both extracted and unextracted material. The experimental data shown in Tables 4.15 - 4.90 are mean values obtained from three replicate samples for each of the studied species together with results of mean separation test.

Differences in desorption equilibrium moisture content between extracted and unextracted *Acacia nilotica* wood was significant only at 20.5 % relative humidity. The unextracted wood had a higher value than the extracted wood (Table 4.15). Significant differences in adsorption equilibrium moisture

content were evident at 75% and 20.5% relative humidity. Similarly, the unextracted wood had higher values than the extracted (Table 4.15).

In *Acacia senegal,* significant differences were found at 50% relative humidity for desorption and at 67.0 % and 50% relative humidity for adsorption equilibrium moisture content (Table 4.16). The unextracted wood was in all cases associated with the higher values of equilibrium moisture content.

No significant differences in desorption or adsorption were found between extracted and unextracted wood of *Anogeissus leiocarpus* (Table 4.17) and *Boswellia papyrifera* (Table 4.18). In *Ailanthus excelsa*, differences between the two groups were significant only at 20.5% relative humidity for both desorption and adsorption equilibrium moisture content; the unextracted wood had significantly the higher equilibrium moisture content in comparison with the extracted wood (Table 4.19).

In *Calotropis procera*, equilibrium moisture content of the unextracted wood was significantly higher than that of the extracted wood for desorption and adsorption at 80.5% and 67% relative humidities, respectively (Table 4.20).

Although the extractives content of the studied species is relatively high (Table 4.14), the above results show that the equilibrium moisture content of extractive free wood is not significantly different from that of unextracted wood. In fact, in the few cases (relative humidity) where there were

significant differences between the two groups, unextracted wood had higher equilibrium moisture content than extracted wood. More over, plotting of the data (Figures 4.41- 4.52) revealed that the relationship between equilibrium moisture content and relative humidity in extracted wood and unextracted wood followed similar trends in the six species.

Many research workers (including Higgins 1957; Nearn 1955; Spalt 1958 and Wangaard 1957) reported that tree species characterized by high extractive content have reduced hygroscopicity, particularly as reflected by the fiber saturation point. Although most workers have attributed this feature to the bulking effect of extractives, little direct evidence of the effect of the removed extractives on sorption isotherms is available.

The results of the current are not in agreement with the findings of Wangaard and Granados (1967), Choong and Achmadi (1989), Skaar (1972) and Koch (1985), who found that the extracted wood exhibited higher equilibrium moisture content than the unextracted wood for both desorption and adsorption. They noted that the hygroscopicity of wood was affected through the extractives bulking the amorphous region in the cell wall. Discrepancies between the results of the current and previous studies can be attributed to differences in the species under study and hence the type and amount of extractives available and to differences in the methodology.

CONCLUSIONS

According to the data and results of this study the following can be concluded

* Relative humidity had more effect on the equilibrium moisture content than temperature.

*The relationship between desorption and adsorption equilibrium moisture content on one hand and relative humidity on the other, exhibited a sigmoid shaped curves.

*Although the relationship can be significantly represented by a linear equation, third-order polynomial equations explain almost all of the variation in equilibrium moisture content.

*The hysteresis between desorption and adsorption isotherms increased with increasing relative humidity.

* At 90 C the hysteresis decrease at higher relative humidities and hysteresis loops close in case of heavier species.

*There were significant differences between species. These differences were greater at higher than at lower relative humidities.

* At the highest relative humidity the species with low wood density had higher equilibrium moisture content than those with high wood density.

* The equilibrium moisture content of extractive free wood was not significantly different from that of unextracted wood.

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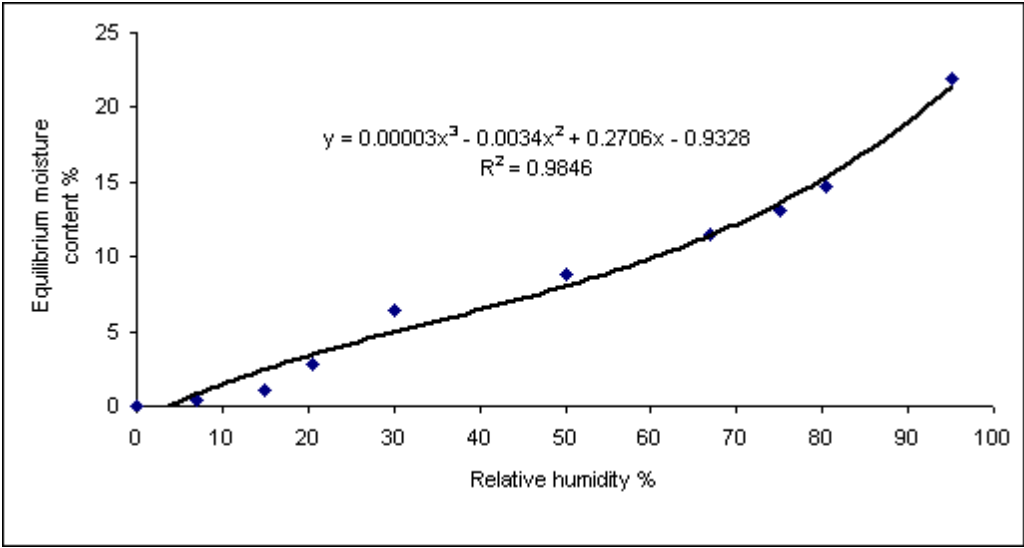
Equilibrium moisture content %

$$y = 0.00003x^3 - 0.0034x^2 + 0.2706x - 0.9328$$
$$R^2 = 0.9846$$

Relative humidity %

Figure 4.14. Desorption isotherm at 60 C for *Acacia senegal*.

Equilibrium moisture content %

$$y = 0.00003x^3 - 0.0026x^2 + 0.2288x - 0.6932$$
$$R^2 = 0.9893$$

Relative humidity %
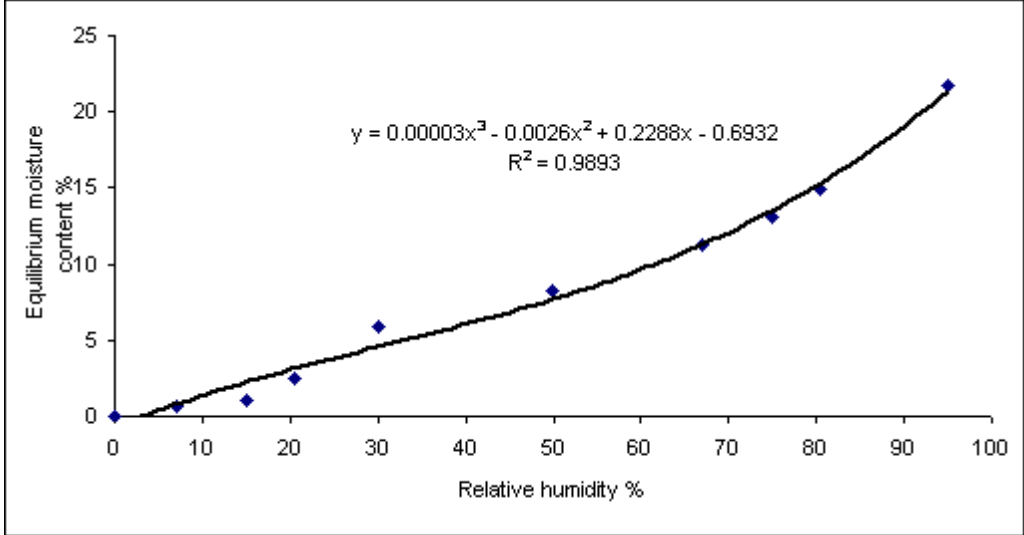
Figure 4.15. Desorption isotherm at 60 C for *Anogeisus leiocarpus*.

$y = 0.00003x^3 - 0.0028x^2 + 0.2248x - 0.7282$
$R^2 = 0.987$
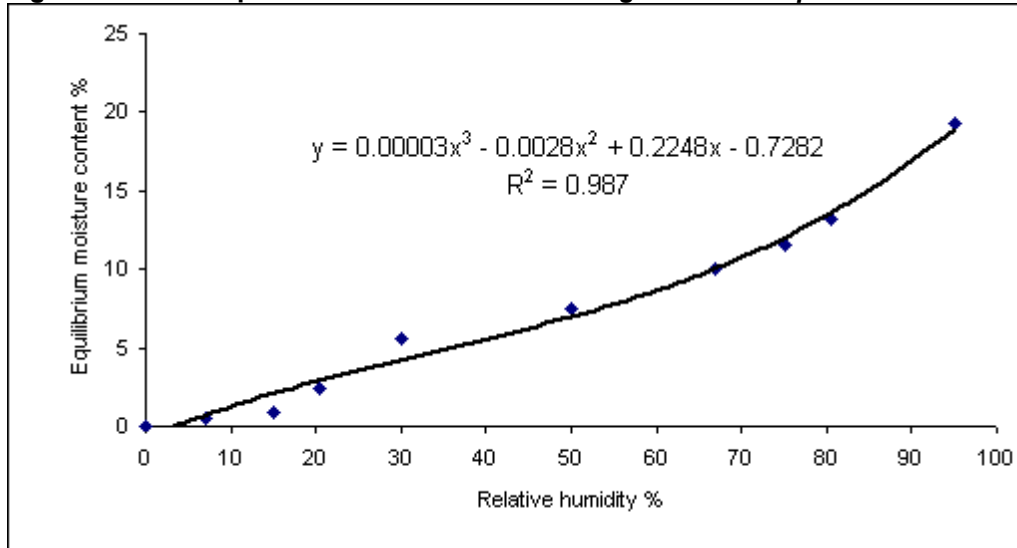
Figure 4.16. Desorption isotherm at 60 C Boswellia papyrifera.

$y = 0.00005x^3 - 0.0051x^2 + 0.2947x - 1.0525$
$R^2 = 0.9834$
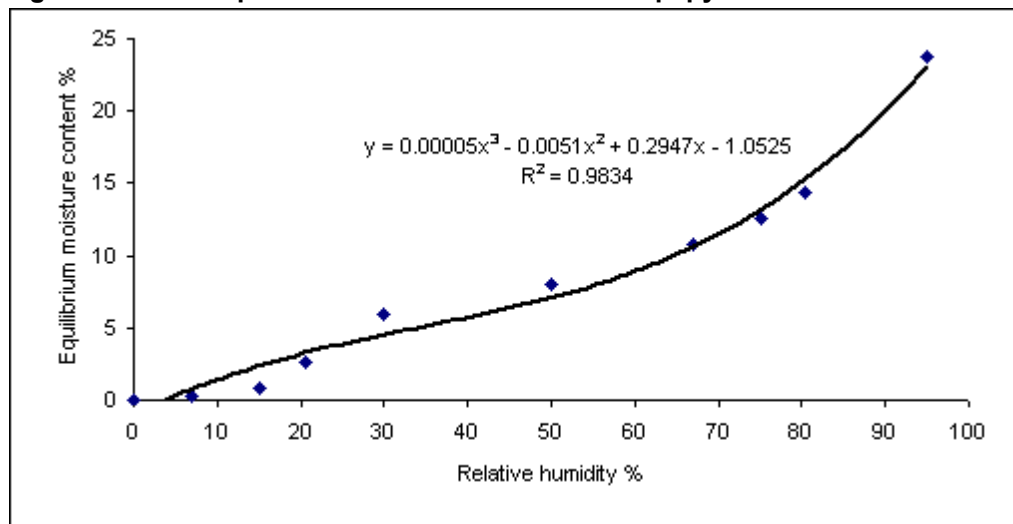
Figure 4.17. Desorption isotherm at 60 C for *Ailanthus excelsa.*

$y = 0.00004x^3 - 0.0046x^2 + 0.2901x - 1.1916$
$R^2 = 0.9821$
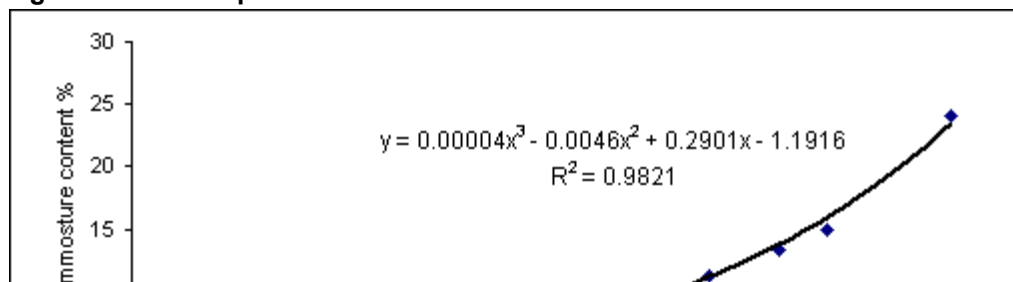
Figure 4.18. Desorption isotherm at 60 C for *Calotropis procera.*

The equation shown on the graph:
$$y = 0.00006x^3 - 0.0057x^2 + 0.2788x - 1.2363$$
$$R^2 = 0.9778$$
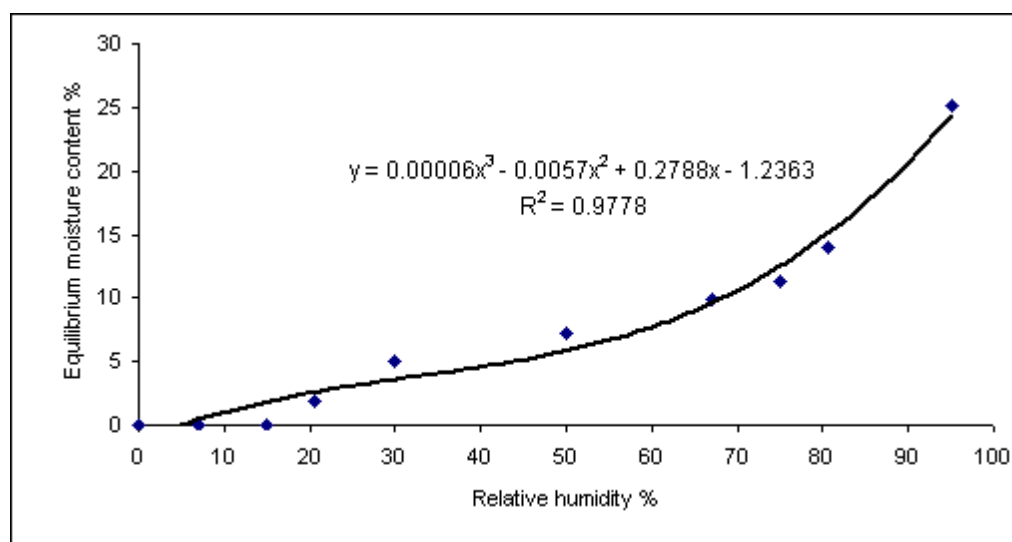
Figure 4.19. Adsorption isotherm at 60 C for *Acacia nilotica.*

The equation shown on the graph:
$$y = 0.00001x^3 - 0.0011x^2 + 0.1528x - 0.7393$$
$$R^2 = 0.9795$$
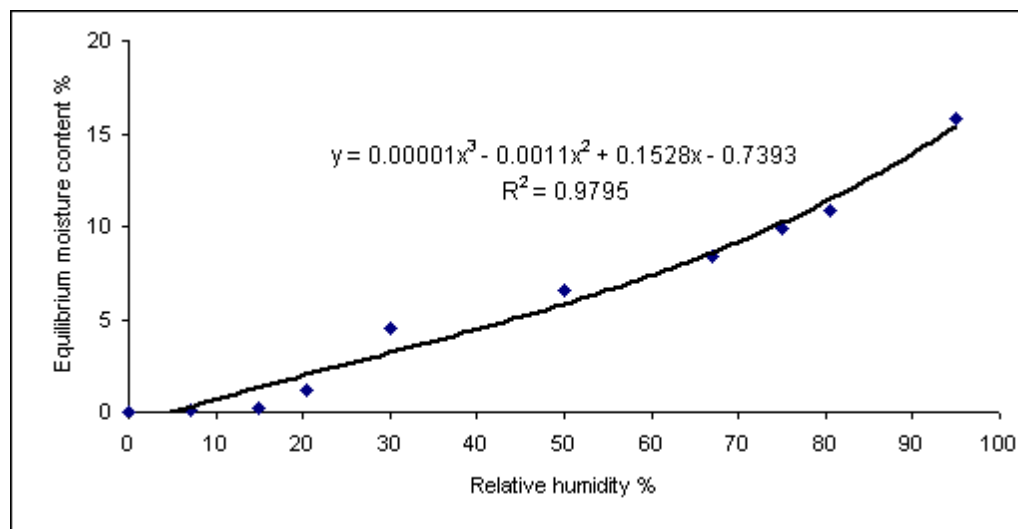
Figure 4.20. Adsorption isotherm at 60 C for *Acacia senegal.*

$$y = 0.00002x^3 - 0.002x^2 + 0.1714x - 0.8356$$
$$R^2 = 0.9784$$
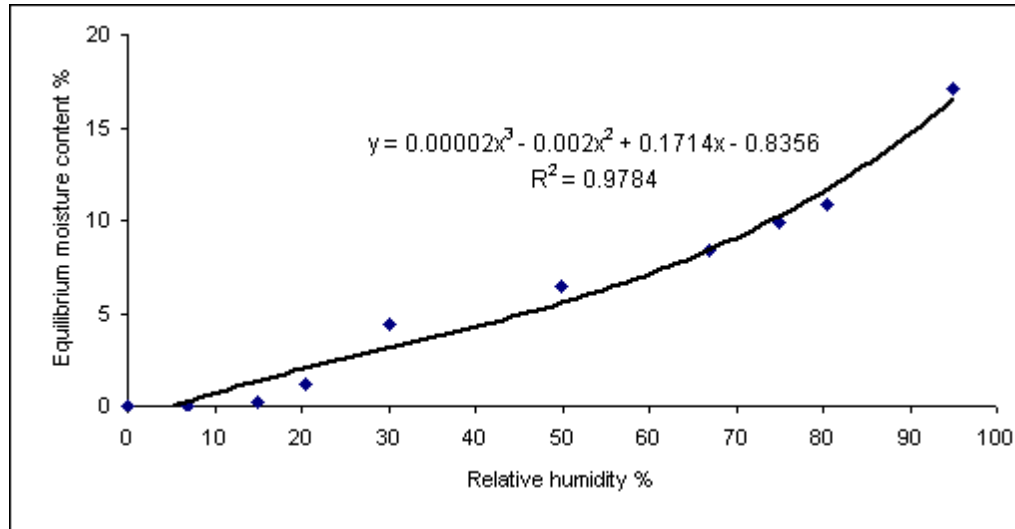
Figure 4.21. Adsorption isotherm at 60 C for *Anogeisus leiocarpus*.

$$y = 0.00001x^3 - 0.0012x^2 + 0.1369x - 0.6443$$
$$R^2 = 0.9803$$
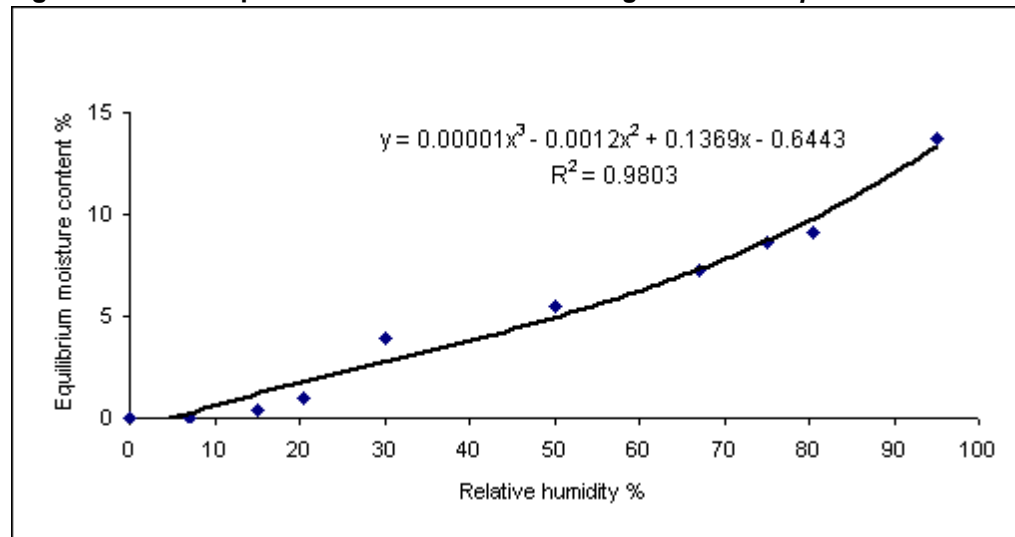
Figure 4.22. Adsorption isotherm at 60 C for *Boswellia papyrifera*.

$$y = 0.00003x^3 - 0.0029x^2 + 0.1934x - 0.8974$$
$$R^2 = 0.9777$$
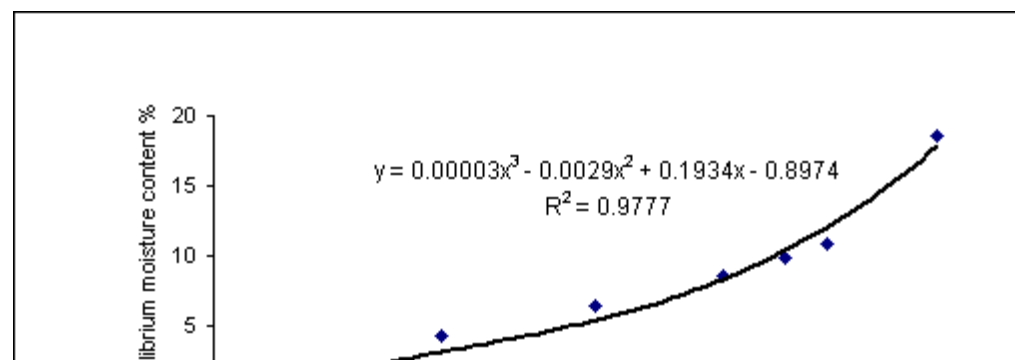
Figure 4.23. Adsorption isotherm at 60 C for *Ailanthus excelsa*.
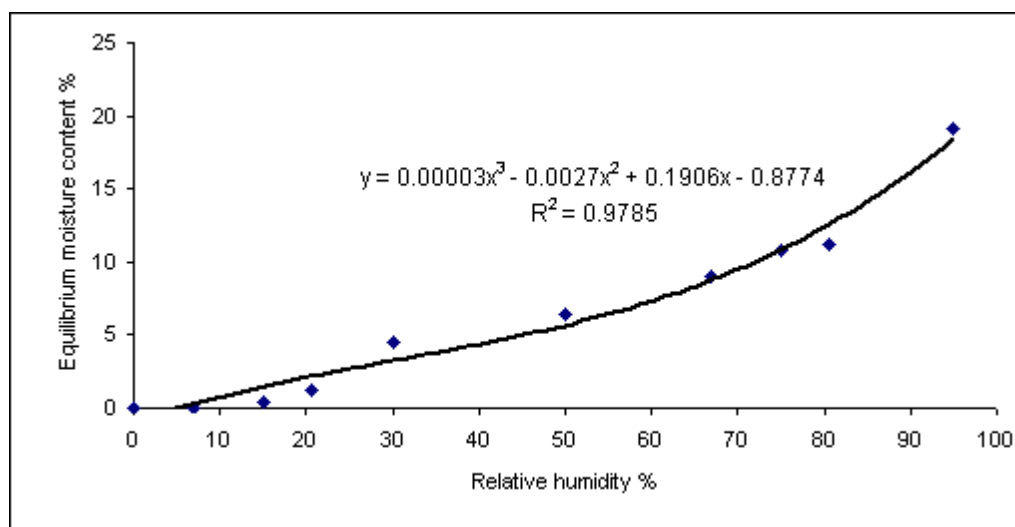
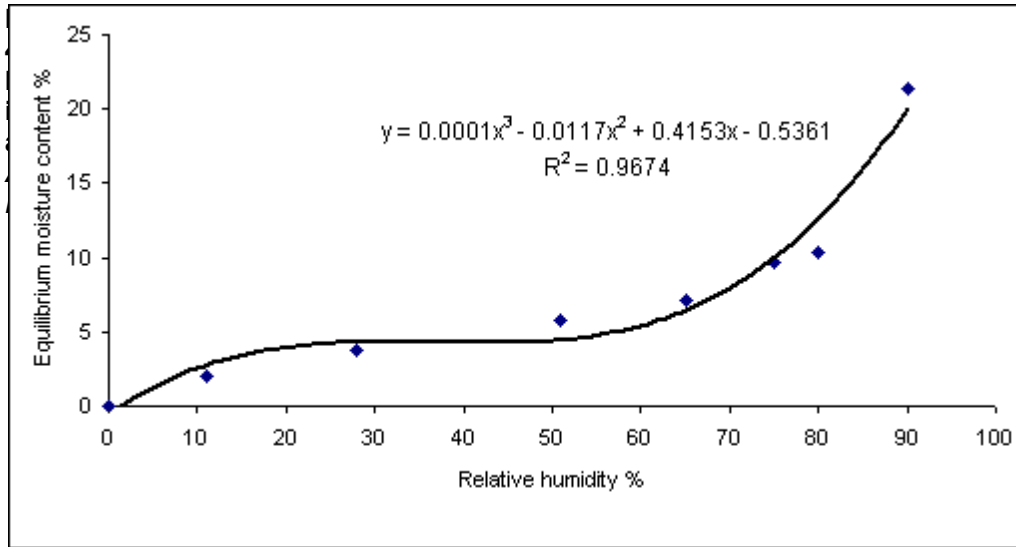**Figure 4.24. Adsorption isotherm at 60 C for *Calotropis procera*.**
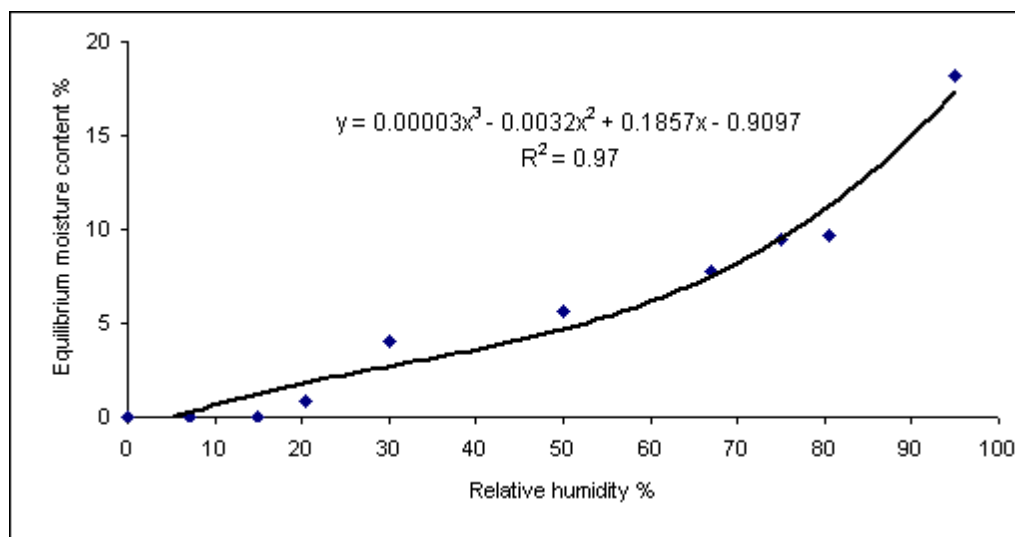
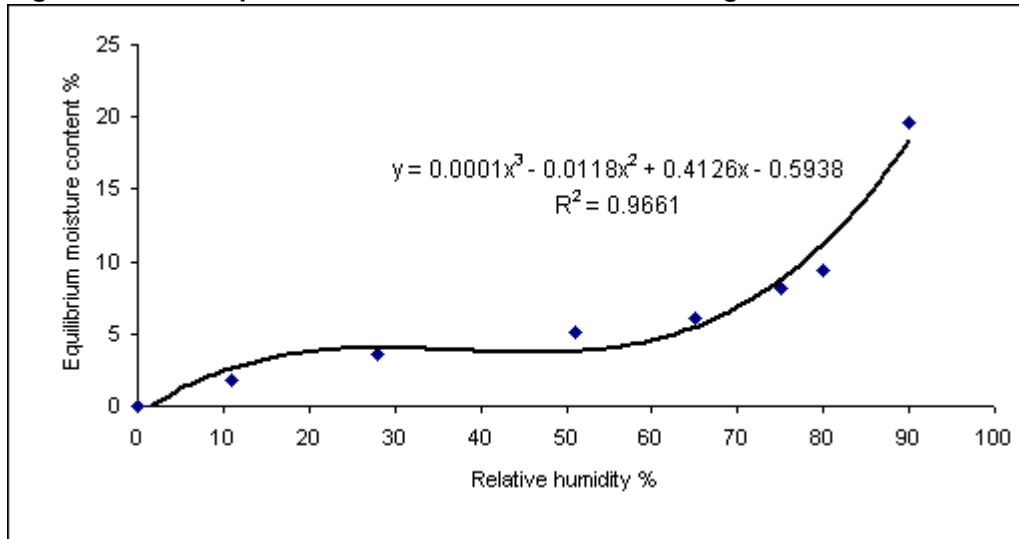**Figure 4.26. Desorption isotherm at 90 C for *Acacia senegal.***

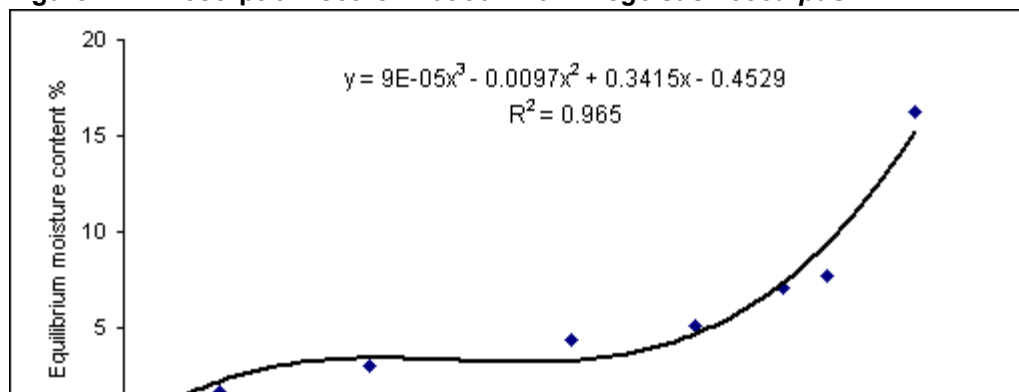**Figure 4.27. Desorption isotherm at 90 C for *Anogeisus lieocarpus.***

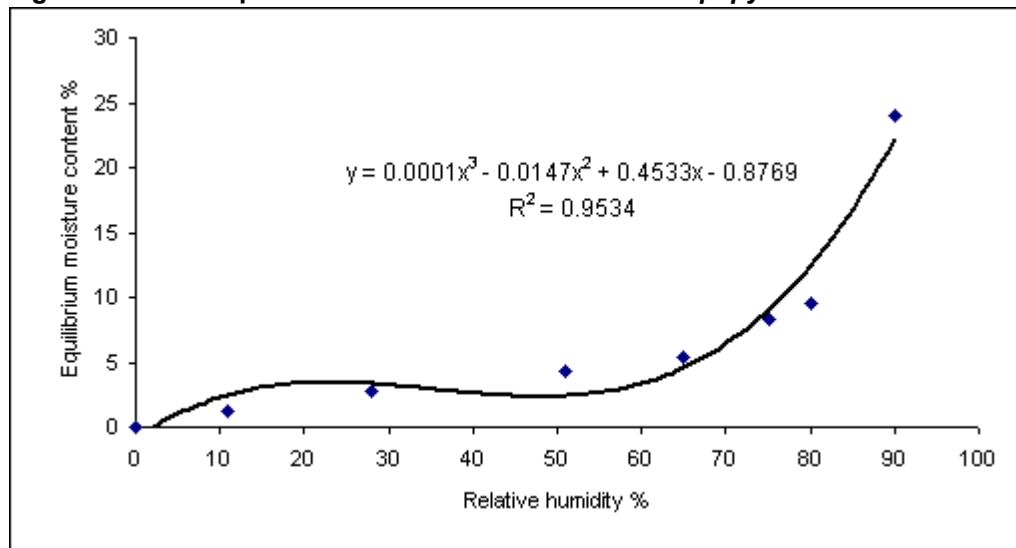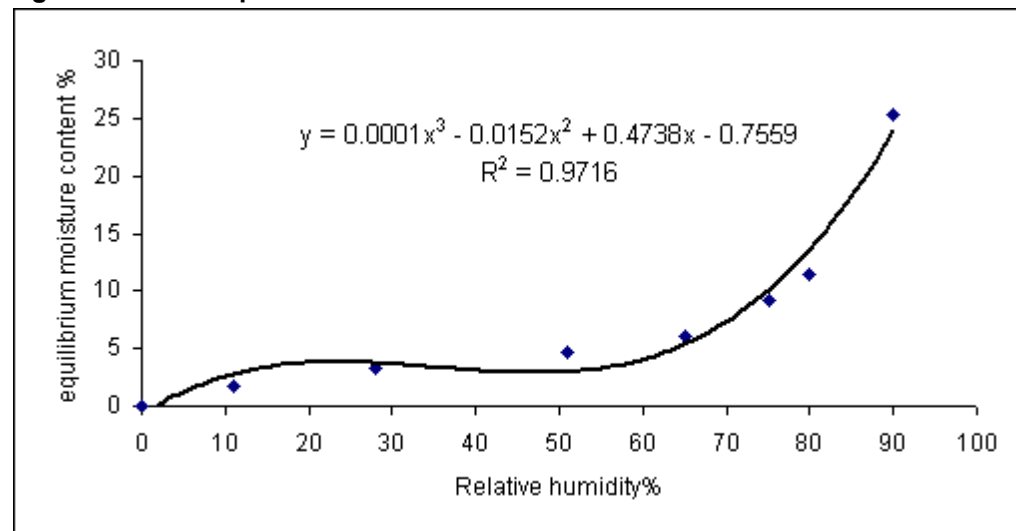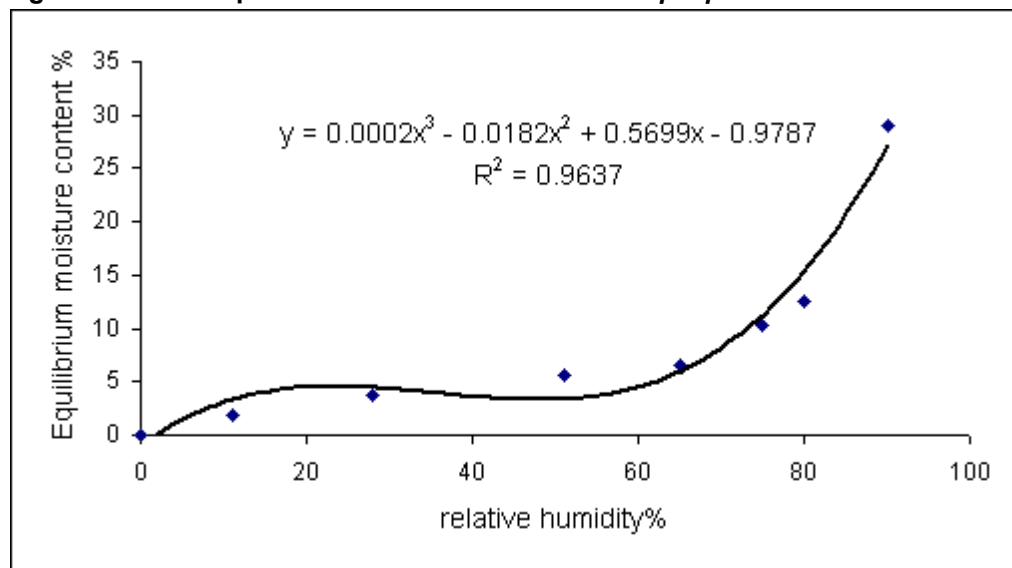**Figure 4.28. Desorption isotherm at 90 C for *Boswellia papyrifera*.**

Figure shows data points with fitted curve.
$$y = 0.0001x^3 - 0.0147x^2 + 0.4533x - 0.8769$$
$$R^2 = 0.9534$$

Axes: Equilibrium moisture content % (y-axis), Relative humidity % (x-axis).

Figure 4.29. Desorption isotherm at 90 C for *Ailanthus ecelsa*.

Figure shows data points with fitted curve.
$$y = 0.0001x^3 - 0.0152x^2 + 0.4738x - 0.7559$$
$$R^2 = 0.9716$$

Axes: equilibrium moisture content % (y-axis), Relative humidity% (x-axis).

Figure 4.30. Desorption Isotherm at 90 C for *Calotropis procera.*

$$y = 0.0002x^3 - 0.0182x^2 + 0.5699x - 0.9787$$
$$R^2 = 0.9637$$

Figure 4.31. Adsorption isotherm at 90 C for *Acacia nilotica.*

$$y = 0.0001x^3 - 0.0148x^2 + 0.4527x - 0.8051$$
$$R^2 = 0.9288$$
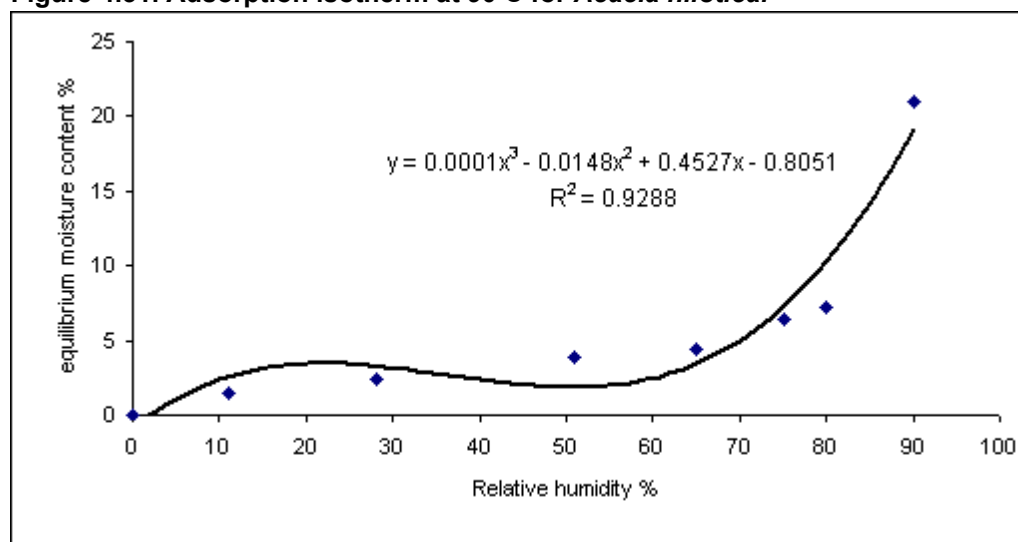
Figure 4.32. Adsorption isotherm at 90 C fo*r Acacia senegal.*

$$y = 0.0001x^3 - 0.014x^2 + 0.4342x - 0.8054$$
$$R^2 = 0.9129$$
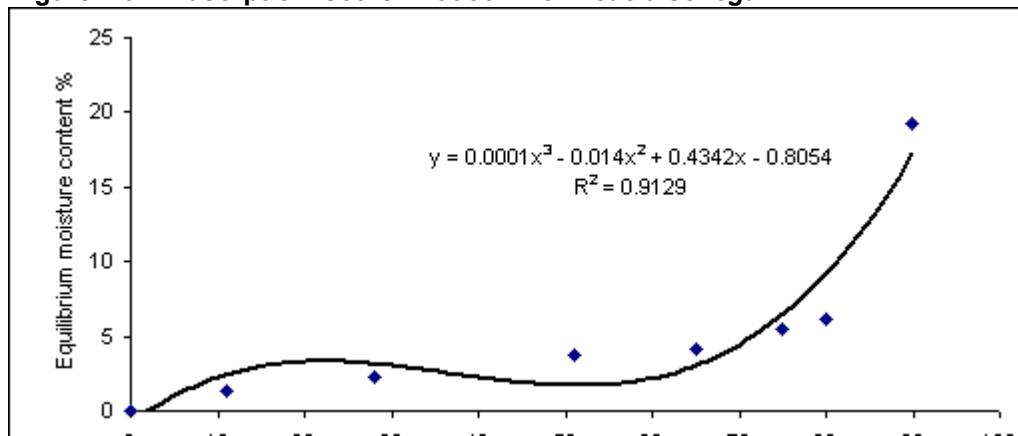
Figure 4.33. Adsorption isotherm at 90 C for *Anogeisus leiocarpus.*

$$y = 0.0001x^3 - 0.0105x^2 + 0.3295x - 0.5491$$
$$R^2 = 0.9323$$

Equilibrium moisture content %

Relative humidity %
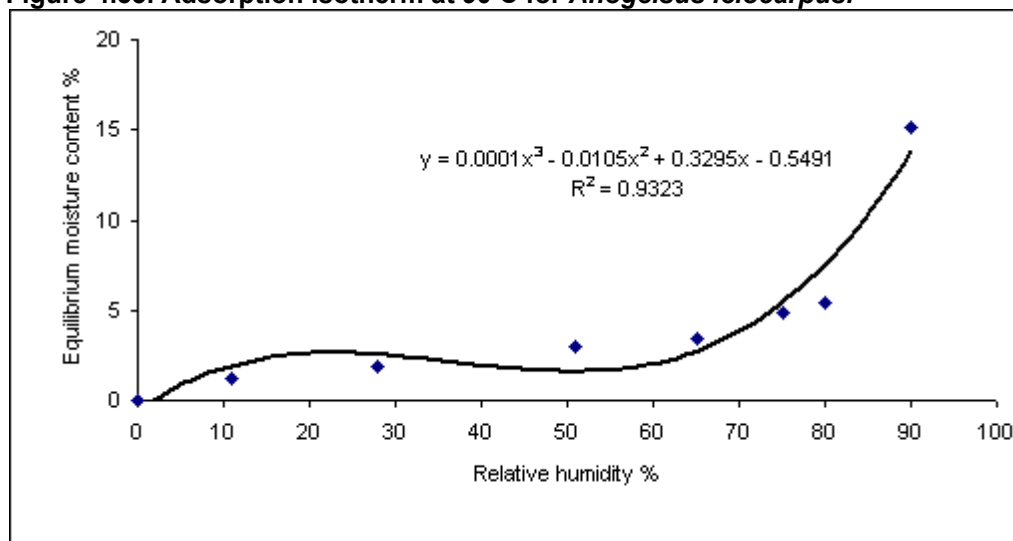
Figure 4.34. Adsorption isotherm at 90 C for *Boswellia papyrifera.*

$$y = 0.0001x^3 - 0.0155x^2 + 0.4489x - 0.9829$$
$$R^2 = 0.8975$$

Equilibrium moisture content %

Relative humidity %
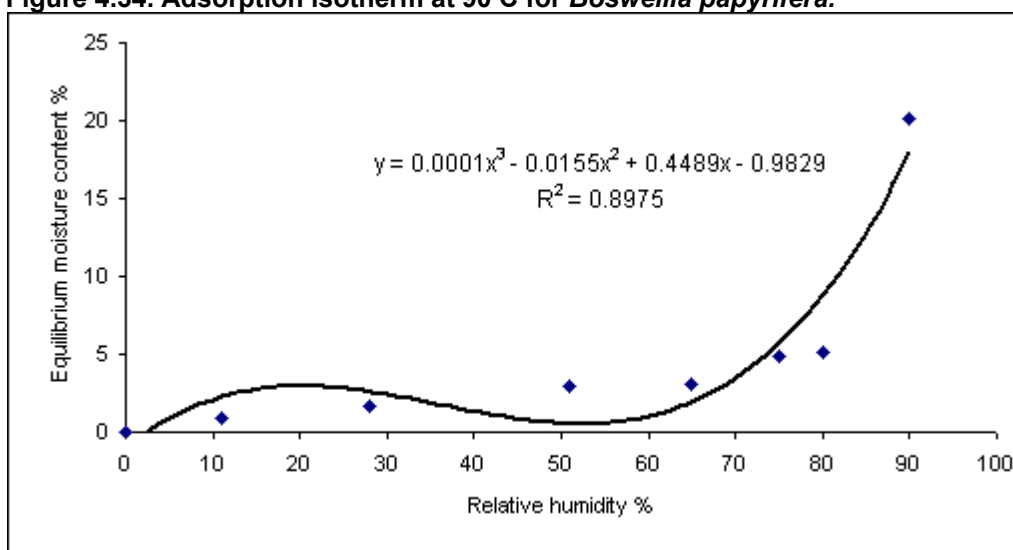
Figure 4.35. Adsorption isotherm at 90 C for *Ailanthus excelsa.*

$y = 0.0002x^3 - 0.0179x^2 + 0.5117x - 1.1656$
$R^2 = 0.9225$
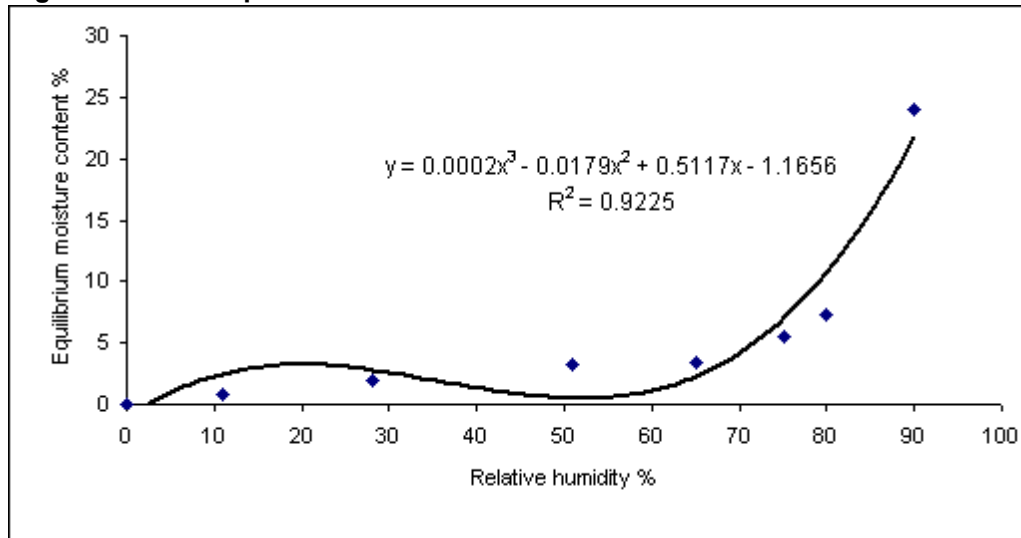
Figure 4.36. Adsorption isotherm at 90 C for *Calotropis procera.*

$y = 0.0002x^3 - 0.0209x^2 + 0.5848x - 1.0216$
$R^2 = 0.912$

Figure 4.1. Desorption and Adsorption isotherms at 60 C in *Acacia nilotica.*

Figure 4.2. Desorption and Adsorption isotherms at 60 C in *Acacia senegal.*

Figure 4.3. Desorption and Adsorption isotherms at 60 C in *Anogeissus leiocarpus.*

Figure 4.4. Desorption and Adsorption isotherms at 60 C in *Boswellia papyreifera*.
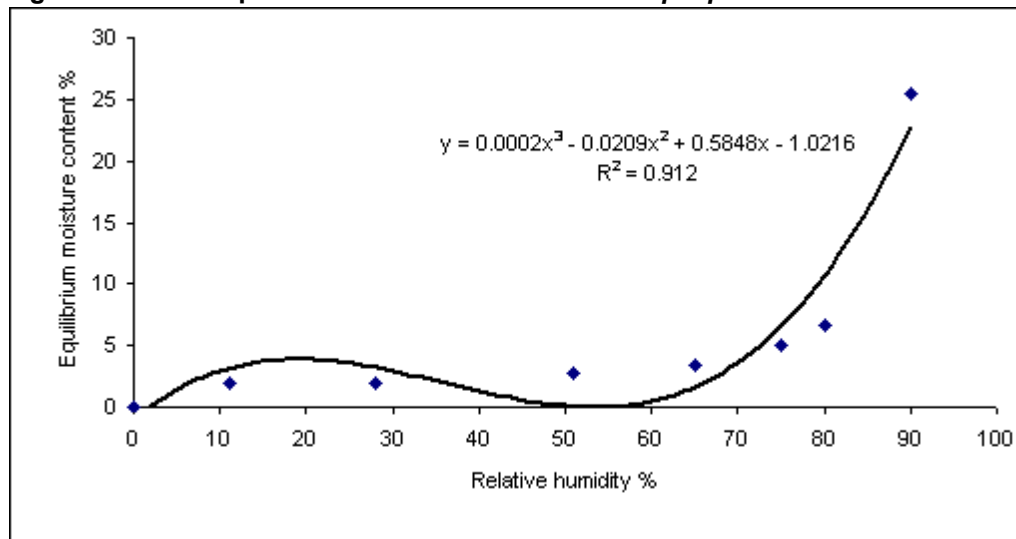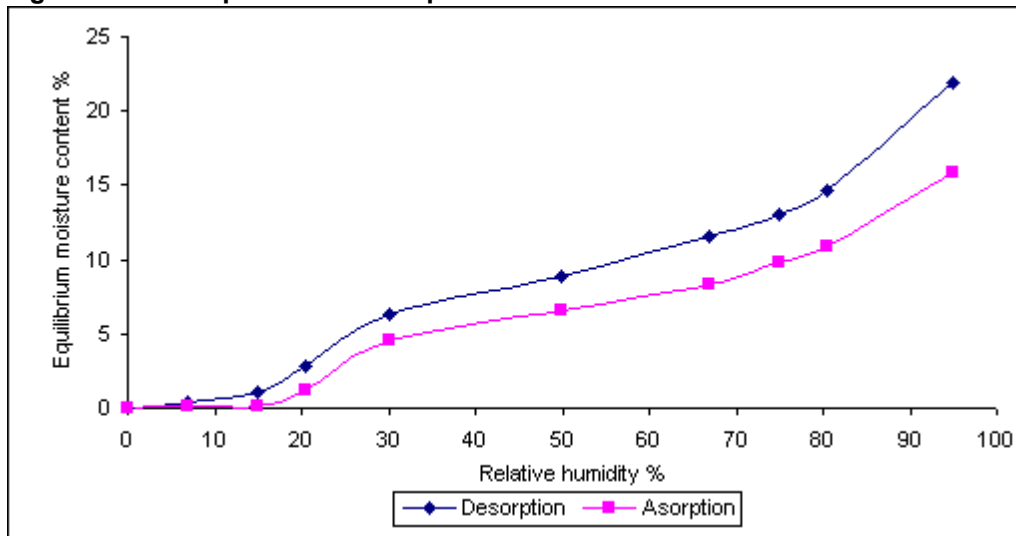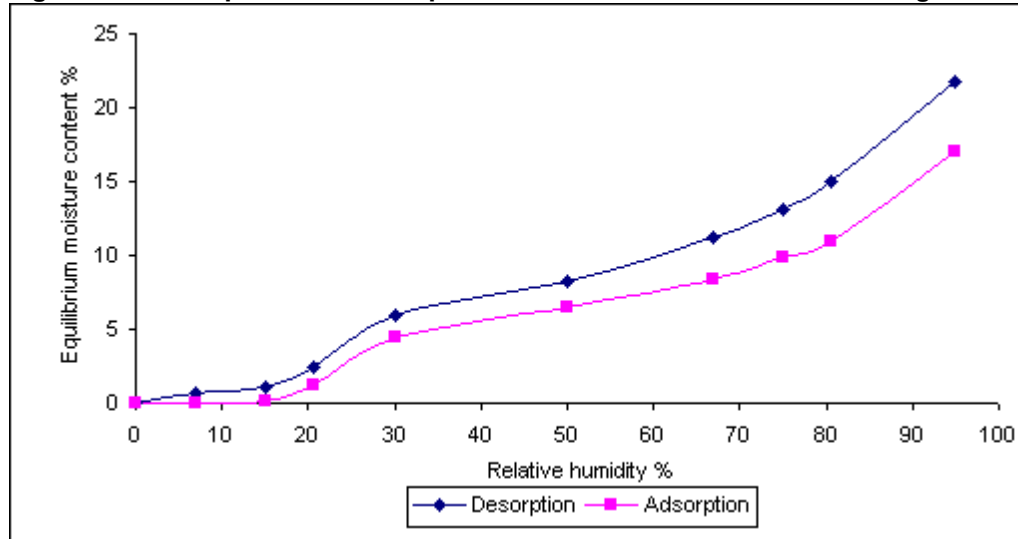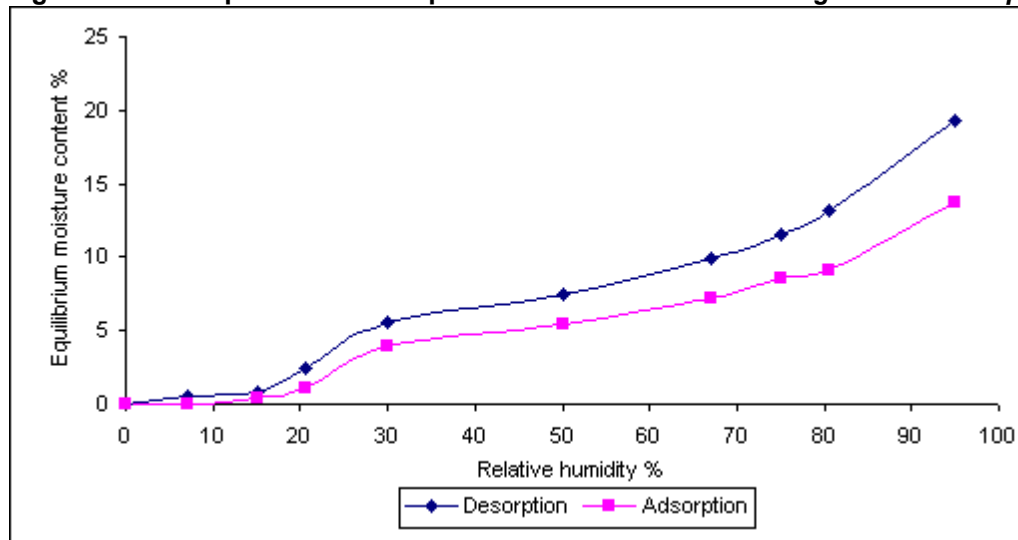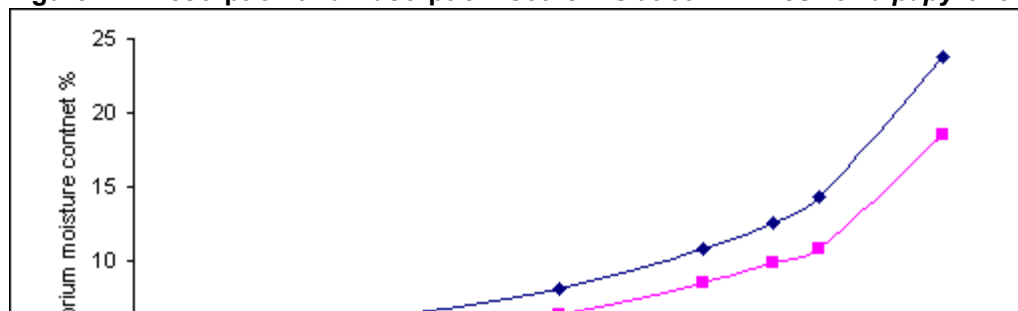
Figure 4.5. Desorption and Adsorption isotherms at 60 C in *Ailanthus excelsa.*
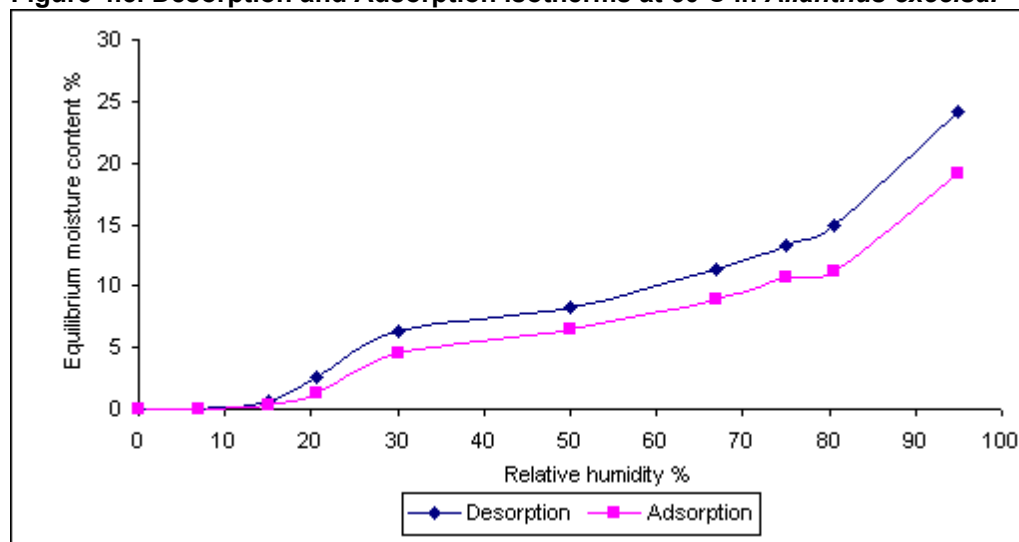
Figure 4.6. Desorption and Adsorption isotherms at 60 C in *Calotropis procera*
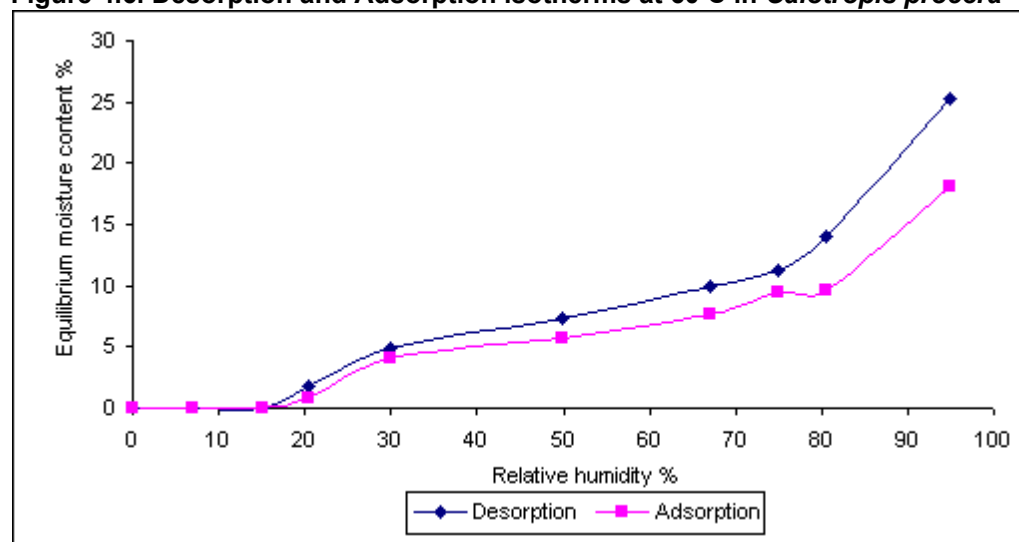
Figure. 4.37. Desorption isotherms at 60 C for six species.

Figure. 4.38. Adsorption isotherms at 60 C for six species.
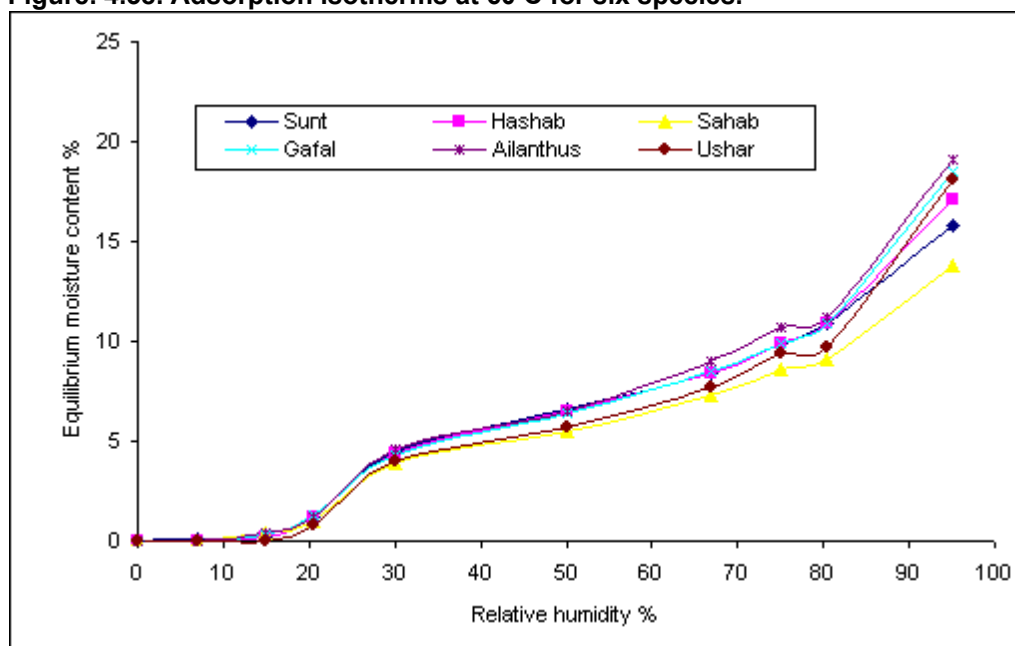
Figure 4.41. Desorption isotherms of extracted and unextracted wood in *Acacia nilotica*.
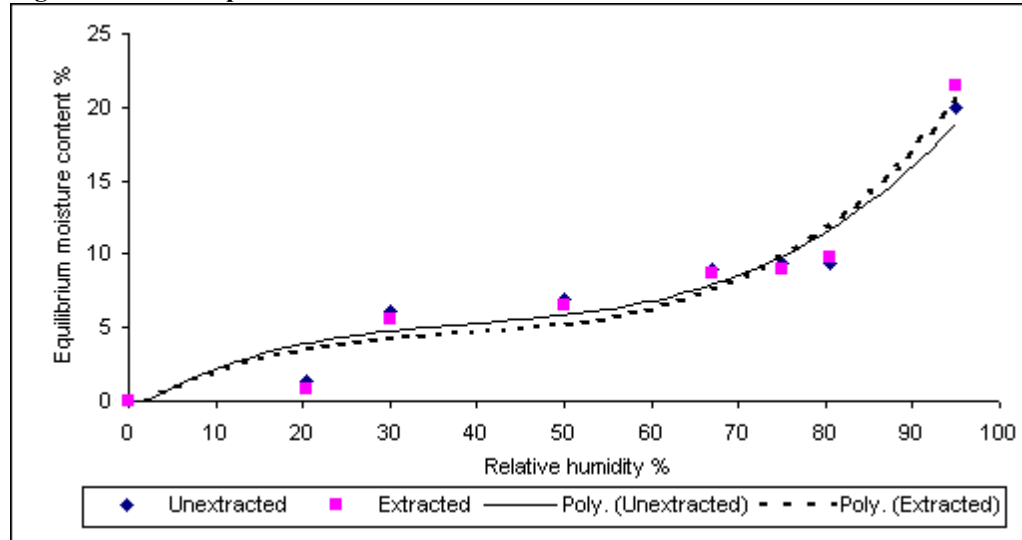
Figure 4.42. Desorption isotherms of extracted and unextracted wood in *Acacia senegal*.
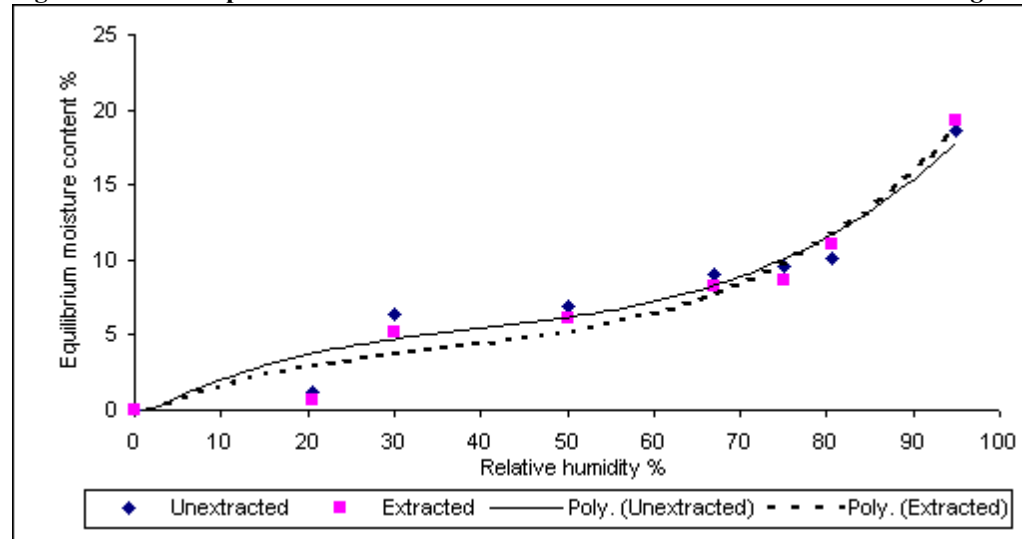
Figure 4.43. Desorption isotherms of extracted and unextracted wood in *Anogeissus leiocarpusl*.
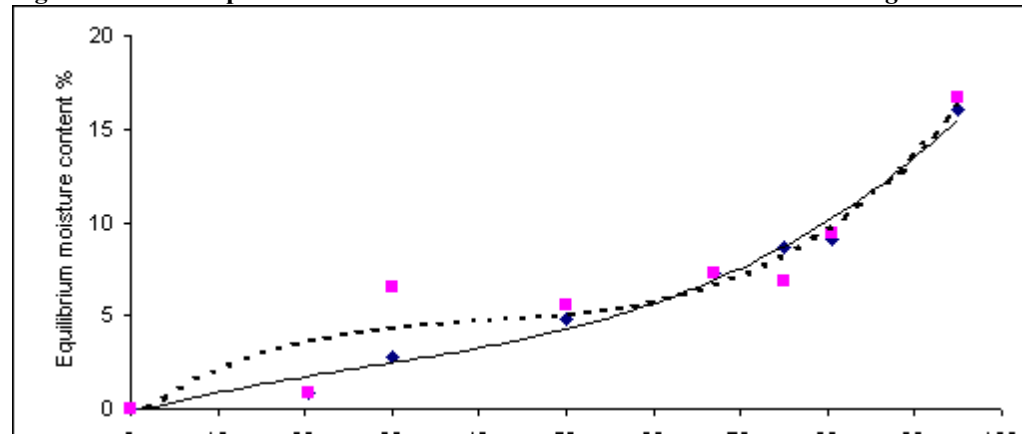
Figure 4.44. Desorption isotherms of extracted and unextracted wood in *Boswellia papyreifera*.
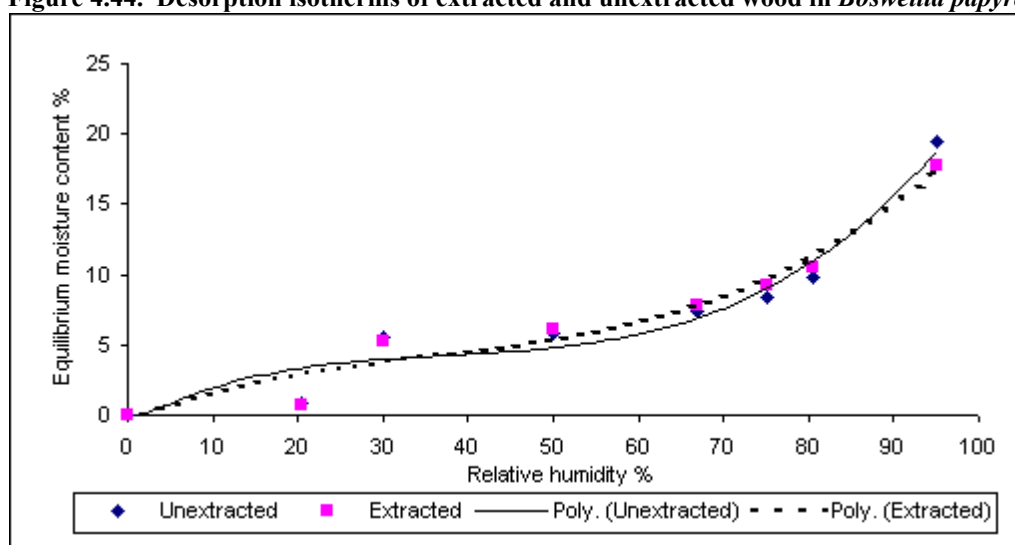
Figure 4.45. Desorption isotherms of extracted and unextracted wood in *Ailanthus excelsa*.
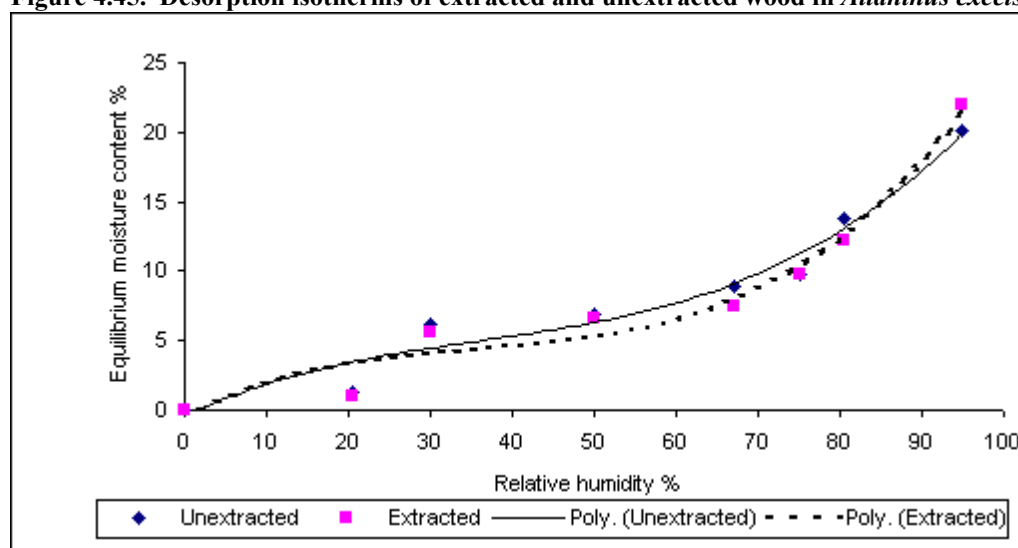
Figure 4.46. Desorption isotherms of extracted and unextracted wood in *Calotropis procera*.
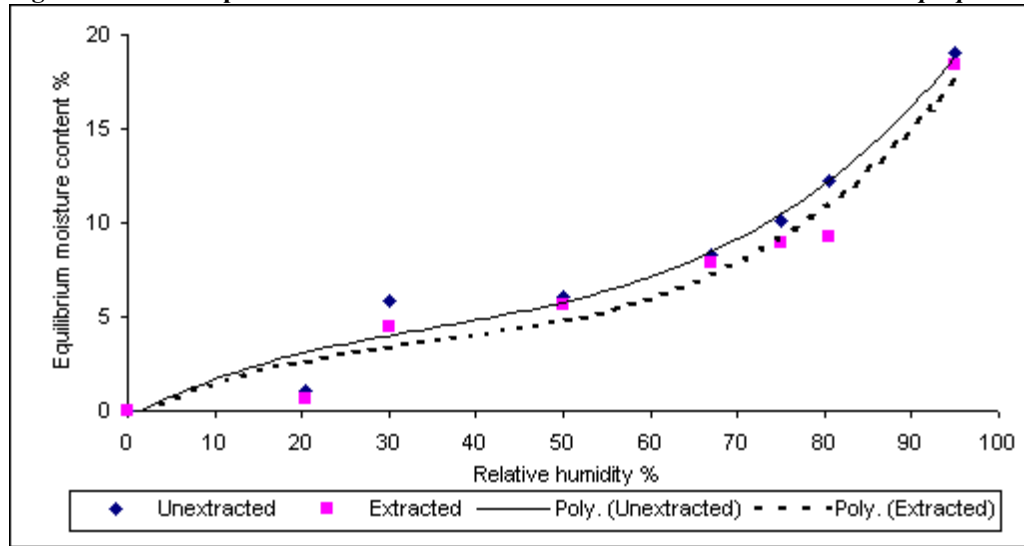
Figure 4.47. Adsorption isotherms of extracted and unextracted wood in *Acacia nilotica*.
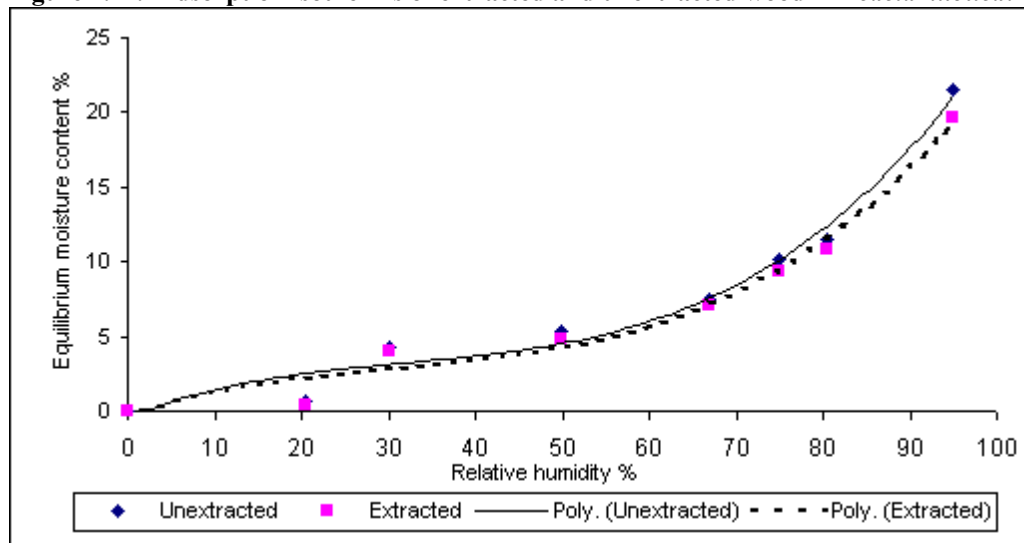
Figure 4.48. Adsorption isotherms of extracted and unextracted wood in *Acacia senegal*.
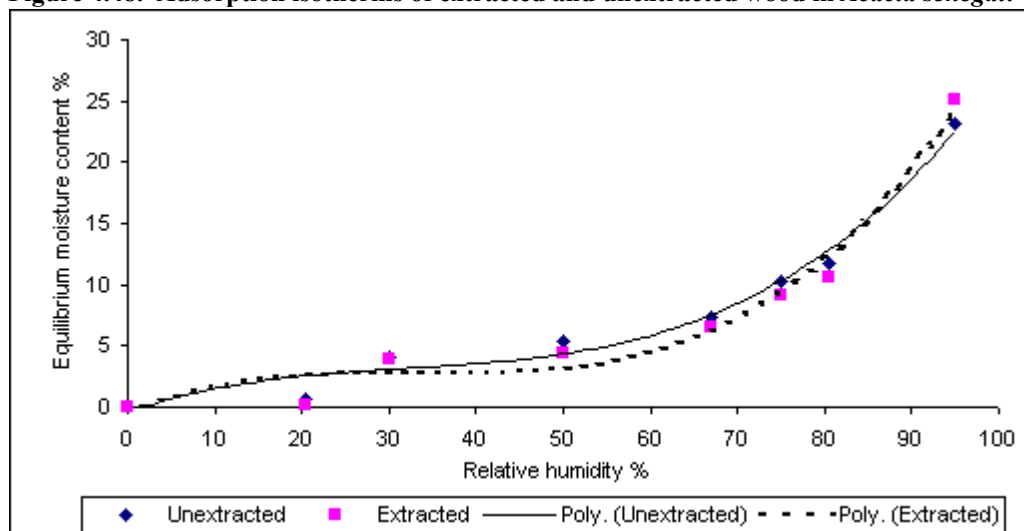
Figure 4.49. Adsorption isotherms of extracted and unextracted wood in *Anogeissus leiocarpus*.
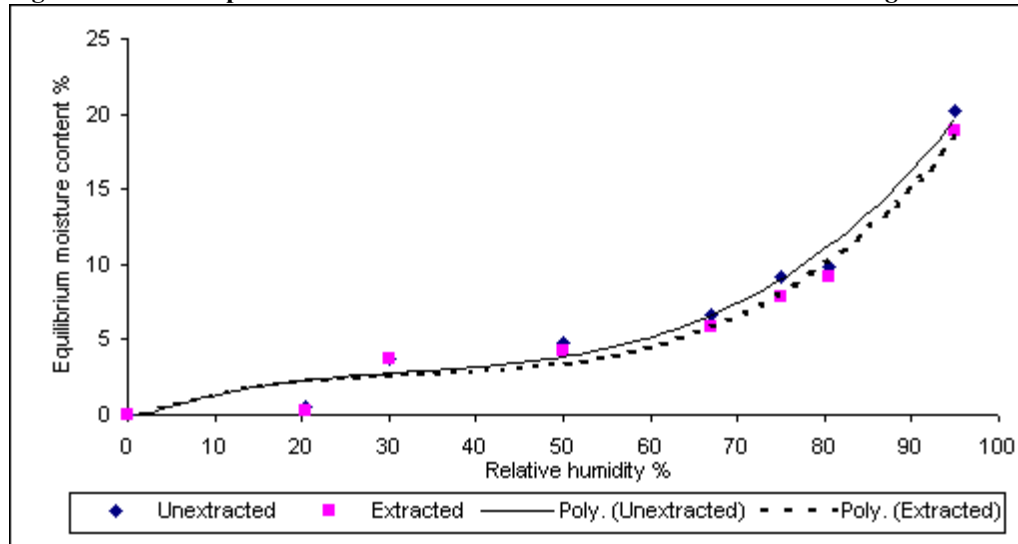
Figure 4.50. Adsorption isotherms of extracted and unextracted wood in *Boswellia papyreifera*.
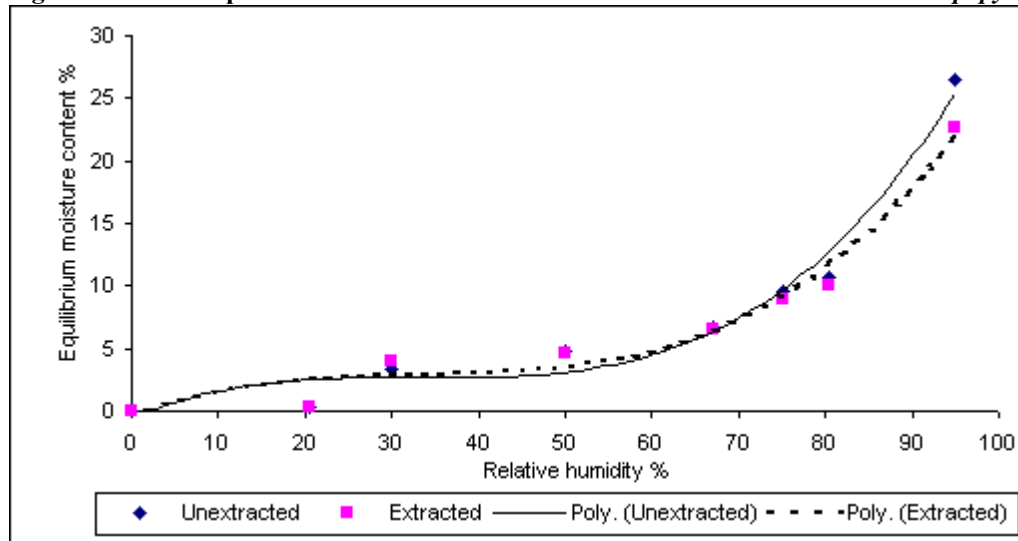
Figure 4.51.Adsorption isotherms of extracted and unextracted wood in *Ailanthus excelsa*.
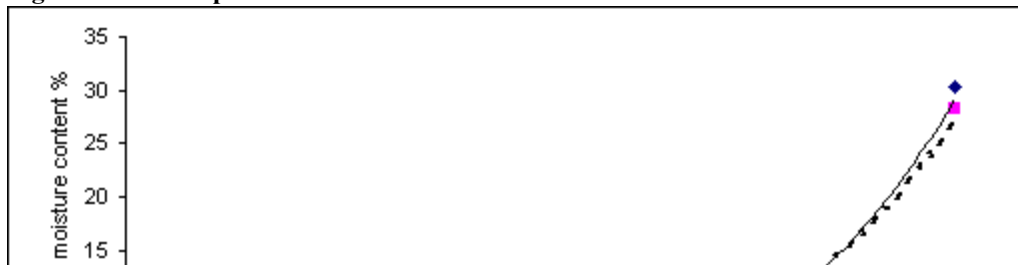
Figure 4.52. Adsorption isotherms of extracted and unextracted wood in *Calotropis procera*.
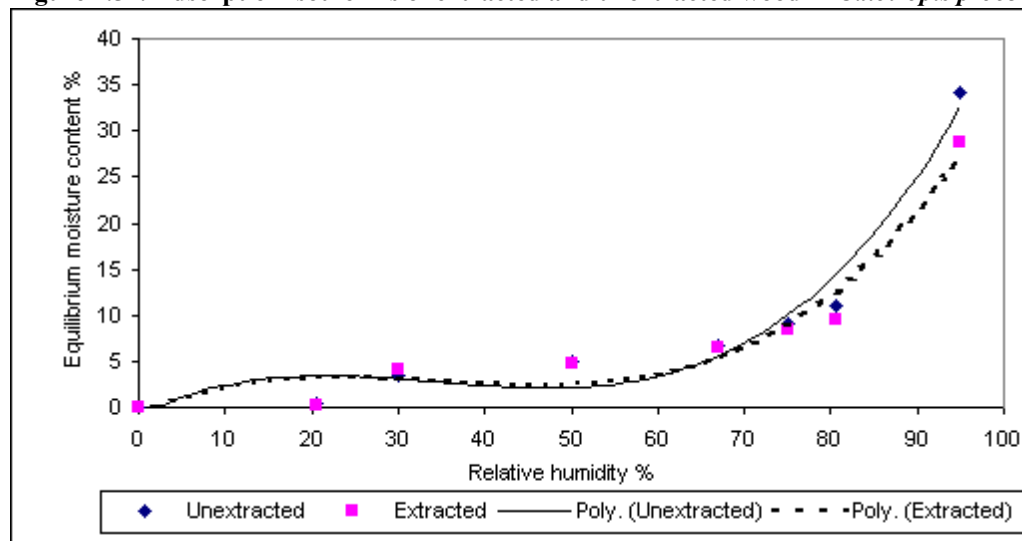
Figure 4.7. Desorption and adsorption isotherms at 90 C in *Acacia nilotica*.
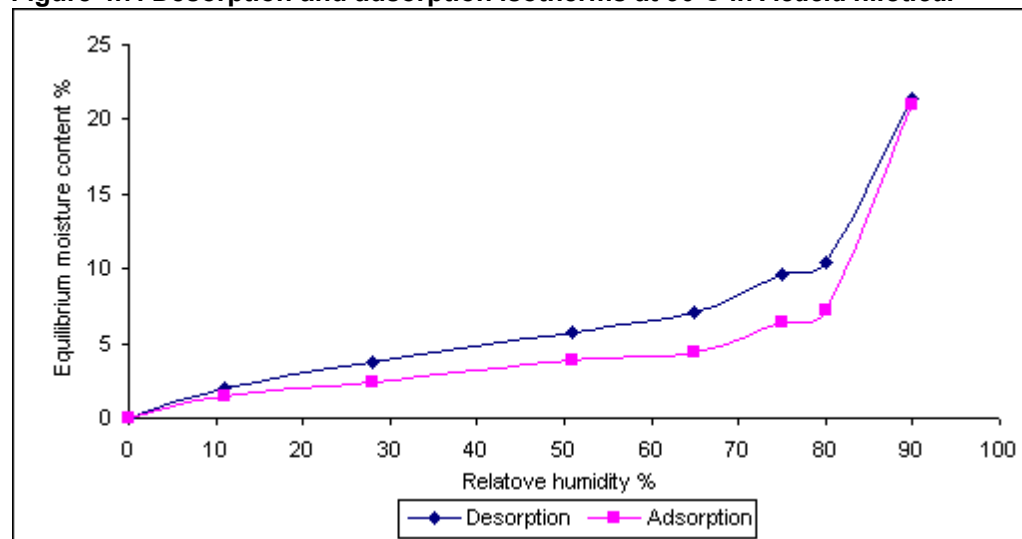
Figure 4.8. Desorption and adsorption isotherms at 90 C in *Acacia senegal*.
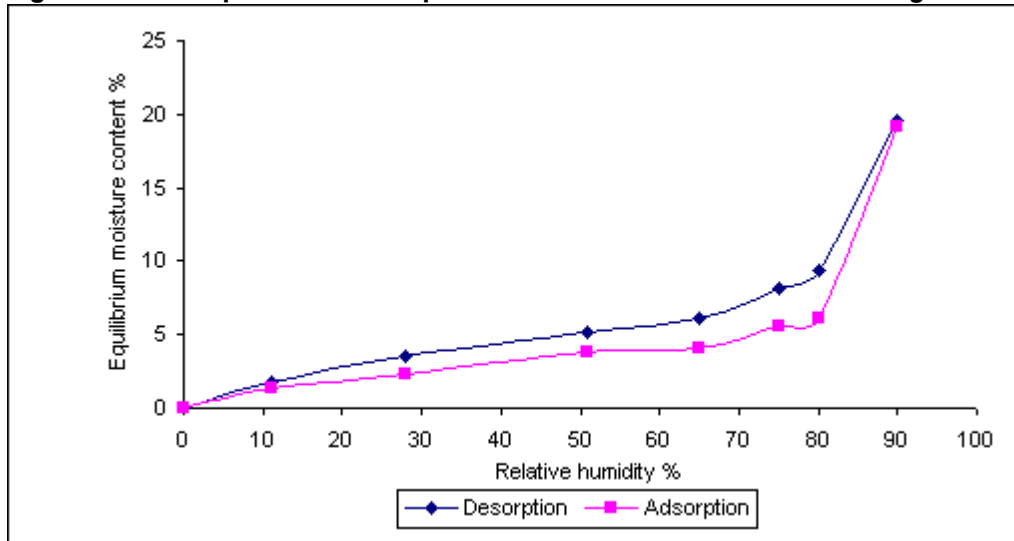
Figure 4.9. Desorption and adsorption isotherms at 90 C in *Anogeissus leicarpusl*.
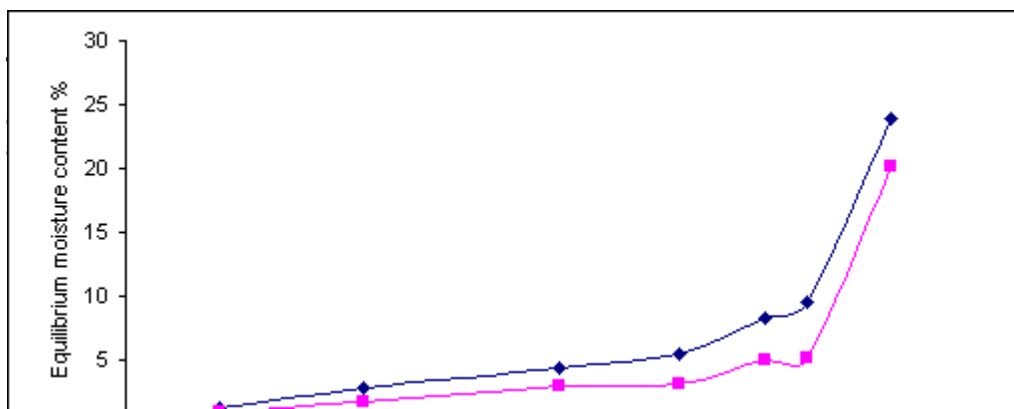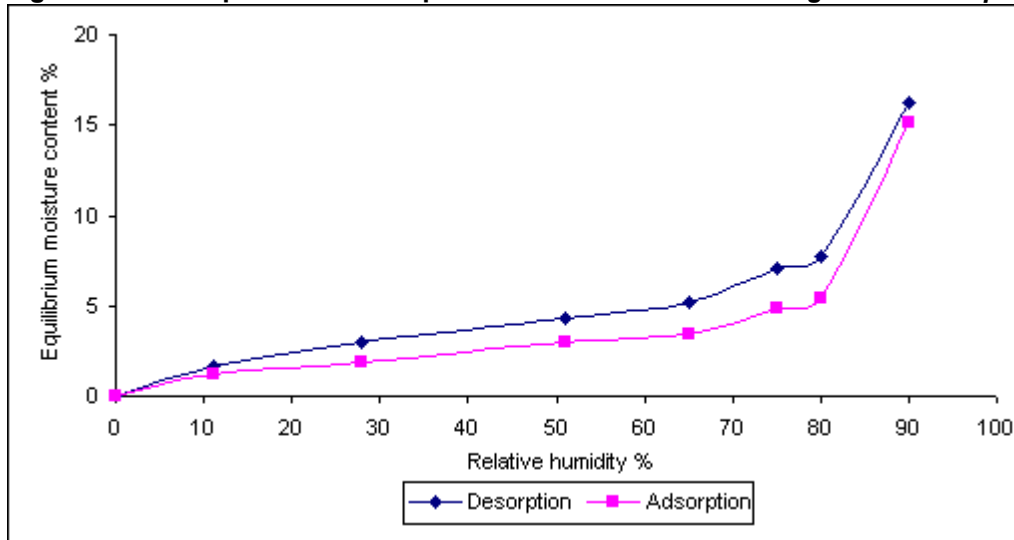
at 90 C in
Boswellia
papyrifera.

Figure 4.11. Desorption and adsorption isotherms at 90 C in *Ailanthus excelsa*.
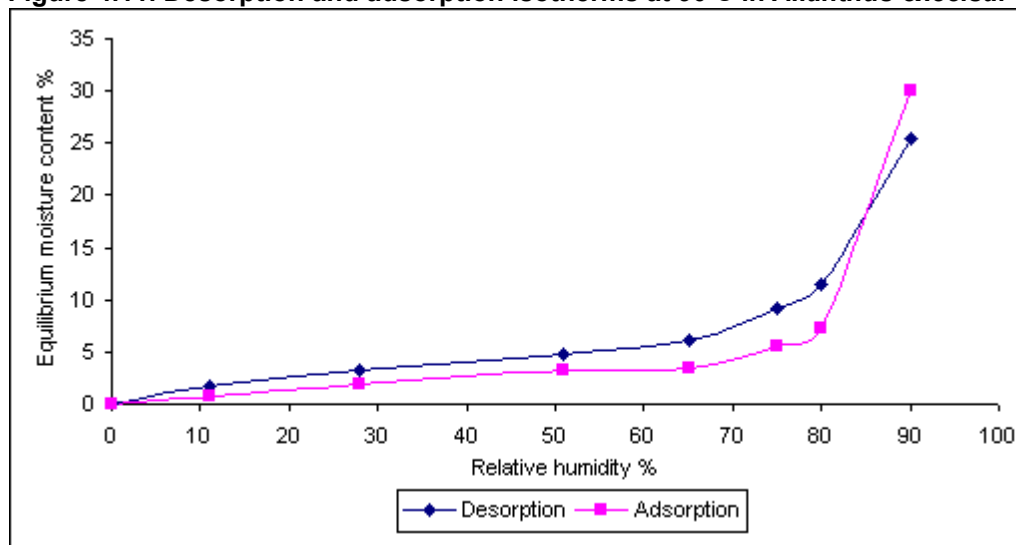
Figure 4.12. Desorption and adsorption isotherms at 90 C in *Calotropis procera.*
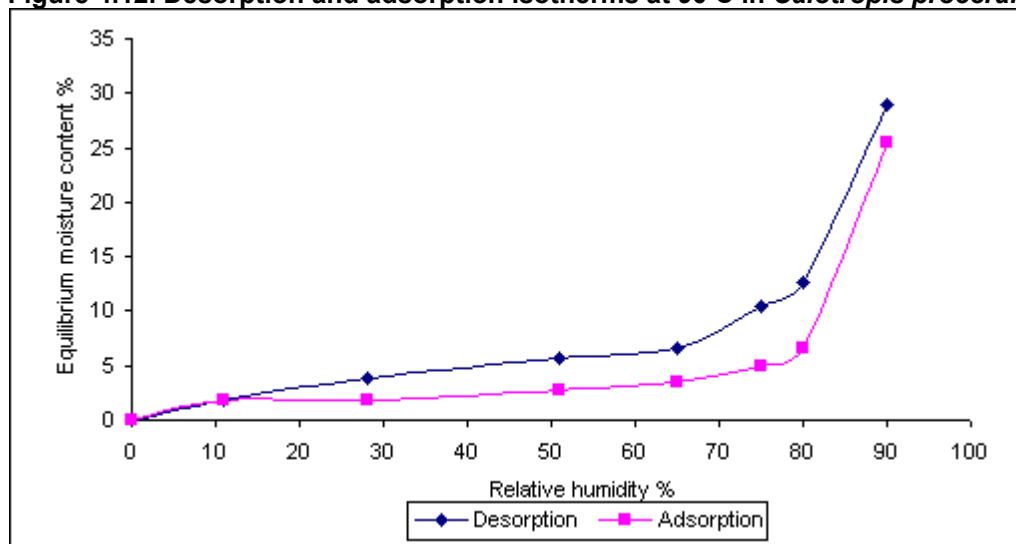
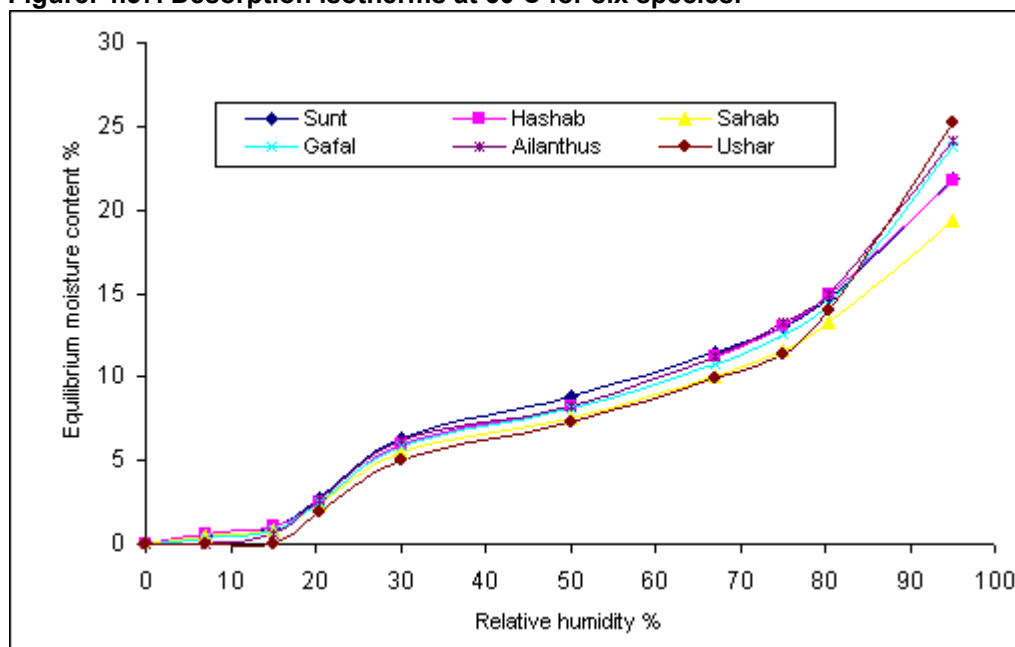**Figure. 4.39. Desorption isotherms at 90 C for six species.**

**Figure. 4.40. Adsorption isotherms at 90 C for six species.**
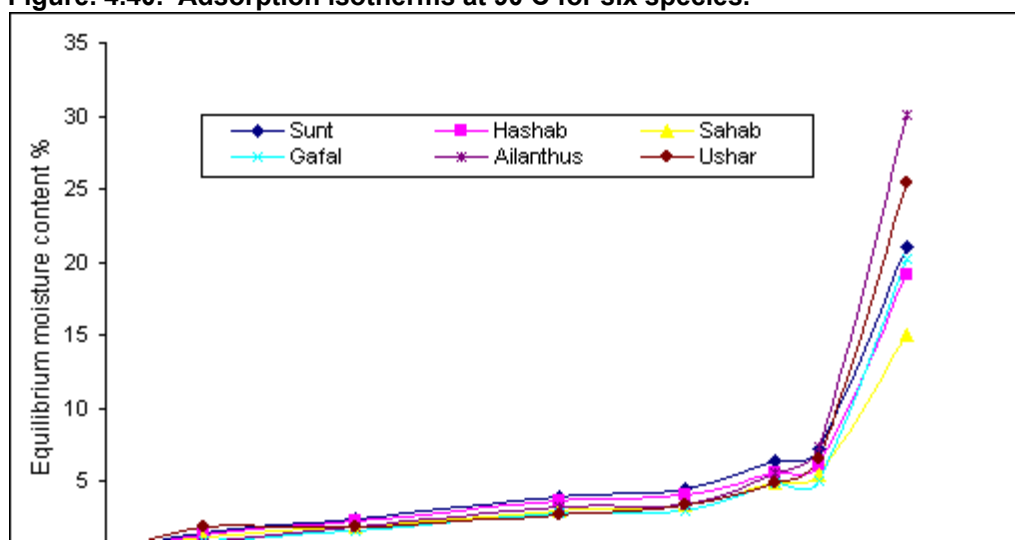
Table 4.1. Wood densities for the six species.

Species	Density (gm / cm^3)		
	Minimum	Means $\pm$ SD	Maximum
Sunt	0.752	0.86 $\pm$ 0.070	0.963
Hashab	0.765	0.862 $\pm$ 0.71	0.994
Sahab	0.766	0.88 $\pm$ 0.066	0.972
Gafal	0.390	0.477 $\pm$ 0.055	0.565
Ailanthus	0.338	0.418 $\pm$ 0.042	0.47
Ushar	0.261	0.297 $\pm$ 0.231	0.333

Table 4.2. The rate of change in desorption equilibrium moisture content in four ranges of relative humidity for the six species at 60 $^{\circ}$C

range	Relative humidity	Rate of change in the different species					
		Sunt	Hashab	Sahab	Gafal	Ailanthus	Ushar
First	0 – 15%	0.0677	0.0677	0.0573	0.0596	0.0383	0
Second	15 – 30%	0.3581	0.3266	0.3133	0.3333	0.3343	0.3333
Third	30 – 75%	0.1477	0.1580	0.1338	0.1466	0.1550	0.1410
Fourth	75 - 95%	0.4450	0.4327	0.3850	0.5637	0.5637	0.6950

Table 4.3. The rate of change in adsorption equilibrium moisture content in four sections of relative humidity for six species at 60 $^{\circ}$C

range	Relative humidity	Rate of change in the different species					
		Sunt	Hashab	Sahab	Gafal	Ailanthus	Ushar
First	0 – 15%	0.0133	0.0133	0.0251	0.0178	0.0266	0
Second	15 – 30%	0.2866	0.2808	0.2346	0.2666	0.2797	0.2666
Third	30 – 75%	0.1188	0.1209	0.1044	0.1244	0.1355	0.1198
Fourth	75 - 95%	0.2950	0.3620	0.2588	0.4313	0.4108	0.4355

Table 4.4. The rate of change in desorption equilibrium moisture content in four sections of relative humidity for six species at 90 $^{\circ}$C

range	Relative humidity	Rate of change in the different species					
		Sunt	Hashab	Sahab	Gafal	Ailanthus	Ushar
First	0 – 11%	0.191	0.1644	0.1450	0.110	0.1557	0.1727
Second	11 – 80%	0.1205	0.1100	0.0880	0.1210	0.1422	0.1546
Third	80 – 90%	1.096	1.0192	0.8582	1.4367	1.390	1.6368

Table 4.5. The rate of change in adsorption equilibrium moisture content in four sections of relative humidity for six species at 90 °C

range	Relative humidity	Rate of change in the different species					
		Sunt	Hashab	Sahab	Gafal	Ailanthus	Ushar
First	0 – 11%	0.1364	0.1272	0.1111	0.0818	0.0818	0.1727
Second	11 – 80%	0.0826	0.0696	0.0609	0.0609	0.0928	0.0681
Third	80 – 90%	1.383	1.3049	0.9687	1.5048	2.7378	1.8756

Table 4.6. Regression models for equilibrium moisture content (EMC) on the relative humidity (RH) relationships at 60 $^{\circ}$C.

Species	Equations	Probability	R^2
Sunt	**EMC = - 1.590 + 0.216 RH (Desorption)** **EMC = - 1.711 + 0.166 RH (Adsorption)**	0.0001 0.0001	0.931 0.924
Hashab	EMC = - 1.853 + 0.218 RH (Desorption) EMC = - 1.995 + 0.174 RH (Adsorption)	0.0001 0.0001	0.946 0.936
Sahab	EMC = - 1.526 + 0.192 RH (Desorption) EMC = - 1.463 + 0.142 RH (Adsorption)	0.0001 0.0001	0.914 0.940
Gafal	EMC = - 2.301 + 0.227 RH (Desorption) EMC = - 2.218 + 0.182 RH (Adsorption)	0.0001 0.0001	0.894 0.907
Ailanth us	EMC = - 2.450 + 0.235 RH (Desorption) **EMC = - 2.290 + 0.189 RH (Adsorption)**	0.0001 0.0001	0.914 0.905
Ushar	EMC = - 3.287 + 0.237 RH (Desorption) EMC = - 2.384 + 0.174 RH (Adsorption)	0.0001 0.0001	0.860 0.855

Table 4.7. Regression models for equilibrium moisture content (EMC) on the relative humidity (RH) relationships at 90 $^{\circ}$C.

Species	Equations	Probability	R^2
Sunt	**EMC = - 1.119 + 0.172 RH (Desorption)** **EMC = - 1.621 + 0.150 RH (Adsorption)**	0.005 0.028	0.721 0.582
Hashab	EMC = - 1.020+ 0.155 RH (Desorption) EMC = - 1.388 + 0.134 RH (Adsorption)	0.007 0.032	0.732 0.564
Sahab	EMC = - 0.781 + 0.129 RH (Desorption) EMC = - 1.050 + 0.108 RH (Adsorption)	0.006 0.024	0.738 0.600
Gafal	EMC = - 2.151+ 0.182 RH (Desorption) EMC = - 1.887 + 0.135 RH (Adsorption)	0.0528 0.0170	0.941 0.642
Ailanthus	EMC = - 2.130 + 0.197RH (Desorption) **EMC = - 3.250 + 0.196 RH (Adsorption)**	0.0130 0.0688	0.670 0.450
Ushar	EMC = - 2.347 + 0.221 RH (Desorption) EMC = - 2.254 + 0.163 RH (Adsorption)	0.015 0.070	0.657 0.448

Table 4.8. Regression models for the desorption equilibrium moisture content (EMC) on the temperature relationships.

Species	Equations	Probability	R^2
Sunt	EMC = 9.15 – 0.018 Temp	0.870	0.002
	EMC = 2.95 + 0.194 RH – 0.0571 Temp	0.0001 / 0.183	0.873
Hashab	EMC = 10.4 – 0.040 Temp	0.710	0.009
	EMC = 4.40 + 0.186 RH – 0.777 Temp	0.0001 / 0.079	0.863
Sahab	EMC = 9.98 – 0.0482 Temp	0.610	0.017
	EMC = 4.83 + 0.161 RH – 0.0804 Temp	0.0001 / 0.040	0.864
Gafal	EMC = 9.86 – 0.032 Temp	0.799	0.004
	EMC = 3.41 + 0.202 RH – 0.0727 Temp	0.0001 / 0.218	0.796
Ailanthus	EMC = 8.94 – 0.013 Temp	0.917	0.001
	EMC = 2.12 + 0.213 RH – 0.056 Temp	0.0001 / 0.339	0.812
Ushar	EMC = 4.9 + 0.042 Temp	0.759	0.006
	EMC = - 2.18 + 0.222 RH – 0.0023 Temp	0.0001 / 0.974	0.770

For the equations containing both relative humidity and temperature the first and second probability values are for testing the significance of the regression coefficient of relative humidity and temperature respectively.

Table 4.9. Regression models for the relationship between adsorption equilibrium moisture content (EMC) with temperature (Temp) and relative humidity (RH)

Species	Equations	Probability	R^2
Sunt	EMC = 5.52 + 0.0040 Temp	0.967	0.001
	EMC = 0.56 + 0.155 RH – 0.027Temp	0.0001 / 0.583	0.761
Hashab	EMC = 6.92 – 0.0179 Temp	0.849	0.002
	EMC = 2.06 + 0.152 RH – 0.0482Temp	0.0001 / 0.318	0.764
Sahab	EMC = 6.11 – 0.0193 Temp	0.799	0.004
	EMC = 2.13 + 0.124 RH – 0.0441Temp	0.0001 / 0.227	0.795
Gafal	EMC = 8.30 – 0.0382 Temp	0.703	0.009
	EMC = 3.30 + 0.156 RH – 0.0695 Temp	0.0001 / 0.224	0.716
Ailanthus	EMC = 4.5 + 0.029 Temp	0.840	0.003
	EMC = - 1.79 + 0.197 RH – 0.0105 Temp	0.0001 / 0.916	0.558
Ushar	EMC = 4.92 + 0.011 Temp	0.924	0.001
	EMC = - 0.33 + 0.164 RH – 0.0221 Temp	0.0001 / 0.754	0.630

For the equations containing both relative humidity and temperature the first and second probability values are for testing the significance of the regression coefficient of relative humidity and temperature respectively.

Table 4.10. Desorption equilibrium moisture content of six hardwood species at temperature 60ºC.

Species	Relative humidity								
	95 %	80.5 %	75 %	67 %	50 %	30 %	20.5 %	15 %	7 %
Ushar	25.2 A	14.0 B	11.3 B	9.9 B	7.3 C	5.5 A	1.9 B	0.0 B	0.0 B
Ailanthus	24.1 AB	14.9 A	13.3 A	11.3 AB	8.3 AB	6.3 A	2.7 A	0.6 A	0.0 B
Gafal	23.8 AB	14.3 AB	12.5 AB	10.8 AB	8.1 ABC	5.9 A	2.6 A	0.9 A	0.3 B
Sunt	21.9 BC	14.7 AB	13.0 A	11.5 A	8.8 A	6.4 A	2.8 A	1.0 A	0.5 A
Hashab	21.7 BC	15.0 A	13.1 A	11.2 AB	8.2 ABC	5.9 A	2.5 A	1.0 A	0.6 A
Sahab	19.3 C	13.2 C	11.6 B	10.0B	7.5 BC	5.6 A	2.4 AB	0.9 A	0.5 A

In the same column, means with the same letter are not significantly different from each other at P≤ 0.05

Table 4.11. Adsorption equilibrium moisture content of six hardwood species at temperature 60ºC.

Species	Relative humidity								
	7 %	15 %	20.5 %	30 %	50 %	67 %	75 %	80.5 %	95 %
Ailanthus	0.0 A	0.4 A	1.2 A	4.6 A	6.5 A	9.0 A	10.7 A	11.2 A	19.1 A
Gafal	0.0 A	0.3 A	1.3 A	4.3 A	6.4 A	8.5 A	9.9 AB	10.9 AB	18.5 A
Ushar	0.0 A	0.0 A	0.8 A	4.0 A	5.7 A	7.7 B	9.4 BC	9.7 BC	18.1 AB
Hashab	0.0 A	0.2 A	1.2 A	4.4 A	6.5 A	8.4 A	9.9 AB	10.9 AB	17.1 AB
Sunt	0.1 A	0.2 A	1.2 A	4.5 A	6.6 A	8.4 A	9.9 AB	10.9 AB	15.8 BC
Sahab	0.0 A	0.4 A	1.0 A	3.9 A	5.5 A	7.3 B	8.6 C	9.1C	13.8 C

In the same column, means with the same letter are not significantly different from each other at P≤ 0.05

Table 4.12. Desorption equilibrium moisture content of six hardwood species at temperature 90 ºC.

Species	Relative humidity						
	90 %	80 %	75 %	65 %	51 %	28 %	11 %
Ushar	28.9 A	12.6 A	10.4 A	6.6 AB	5.7 A	3.8 A	1.9 A
Ailanthus	25.4 AB	11.5 B	9.3 B	6.0 BC	4.7 BC	3.2 BC	1.7 A
Gafal	23.9 BC	9.6 C	8.4 C	5.4 CD	4.3 C	2.8 D	1.2 B
Sunt	21.3 CD	10.4 C	9.7 AB	7.1 A	5.8 A	3.7 A	2.1 A
Hashab	19.6 DE	9.4 C	8.1 C	6.1 BC	5.2 AB	3.6 AB	1.8 A
Sahab	16.3 E	7.7 D	7.1 D	5.2 D	4.3 C	3.0 CD	1.6 AB

In the same column, means with the same letter are not significantly different from each other
at P≤ 0.05

Table 4.13. Adsorption equilibrium moisture content of six hardwood species at temperature 90ºC.

Species	Relative humidity						
	11 %	28 %	51 %	65 %	75 %	80 %	90 %
Ailanthus	0.9 C	1.9 BC	3.2 BC	3.4 B	5.6 B	7.3 A	30.4 A
Ushar	1.9 A	1.9 C	2.8 C	3.4 B	5.0 B	6.6 AB	25.4 B
Sunt	1.5 AB	2.4 A	3.9 A	4.5 A	6.4 A	7.2 A	21.1 BC
Gafal	0.9 C	1.7 C	2.9 C	3.1 B	4.9 B	5.1 B	20.2 BC
Hashab	1.4 B	2.3 AB	3.8 AB	4.1 A	5.5 B	6.2 AB	19.2 BC
Sahab	1.2 BC	1.9 BC	3.0 C	3.4 B	4.9 B	5.4 B	15.1 C

In the same column, means with the same letter are not significantly different from each other
at P≤ 0.05

Table 4.14. Extractives content for six species.

Species	Extractives content
Sunt	11.8
Hashab	19.75
Sahab	11.03
Gafal	7.53
Ailanthus	6.57
Ushar	7.58

Table 4.15. Effect of extraction on desorption and adsorption equilibrium moisture content at various level of relative humidity for Sunt (*Acacia nilotica*)

Relative humidity	Extractive content	Desorption	Adsorption
95 %	Unextracted	21.5 A	21.6 A
	Extracted	20.0 A	19.7 A
80.5 %	Unextracted	9.8 A	11.5 A
	Extracted	9.4 A	10.9 A
75 %	Unextracted	9.4 A	10.1 A
	Extracted	9.0 A	9.3 B
67 %	Unextracted	9.0 A	7.5 A
	Extracted	8.7 A	7.0 A
50 %	Unextracted	6.9 A	5.3 A
	Extracted	6.5 A	4.8 A
30 %	Unextracted	6.2 A	4.2 A
	Extracted	5.6 A	4.1 A
20.5 %	Unextracted	1.4 A	0.7 A
	Extracted	0.9 B	0.4 B

Table 4.16. Effect of extraction on desorption and adsorption equilibrium moisture content at various level of relative humidity for Hashab (*Acacia senegal*)

Relative humidity	Extractive content	Desorption	Adsorption
95 %	Unextracted	18.6 A	23.1 A
	Extracted	19.2 A	25.2 A
80.5 %	Unextracted	10.1 A	11.7 A
	Extracted	11.1 A	10.6 A
75 %	Unextracte	9.6 A	10.3 A
	Extracted	8.6 A	9.1 A
67 %	Unextracted	9.1 A	7.4 A
	Extracted	8.3 A	6.6 B
50 %	Unextracted	7.0 A	5.4 A
	Extracted	6.1 B	4.4 B
30 %	Unextracted	6.4 A	4.1 A
	Extracted	5.1 A	4.0 A
20.5 %	Unextracted	1.2 A	0.7 A
	Extracted	0.6 A	0.2 A

Table 4.17. Effect of extraction on desorption and adsorption equilibrium moisture content at various level of relative humidity for Sahab (*Anogeissus leicarpus*)

Relative humidity	Extractive content	Desorption	Adsorption
95 %	Unextracted	16.0 A	20.2 A
	Extracted	16.7 A	18.8 A
80.5 %	Unextracted	9.1 A	9.9 A
	Extracted	9.4 A	9.2 A
75 %	Unextracted	8.7 A	9.2 A
	Extracted	6.9 A	7.8 A
67 %	Unextracted	7.3 A	6.5 A
	Extracted	7.2 A	5.9 A
50 %	Unextracted	4.8 A	4.8 A
	Extracted	5.5 A	4.2 A
30 %	Unextracted	2.8 A	3.7 A
	Extracted	6.5 A	3.7 A
20.5 %	Unextracted	0.9 A	0.6 A
	Extracted	0.8 A	0.3 A

Table 4.18. Effect of extraction on desorption and adsorption equilibrium moisture content at various level of relative humidity for Gafal (*Boswellia papyrifera*)

Relative humidity	Extractive content	Desorption	Adsorption
95 %	Unextracted	19.5 A	26.4 A
	Extracted	17.8 A	22.7 A
80.5 %	Unextracted	9.8 A	10.7 A
	Extracted	10.5 A	10.0 A
75 %	Unextracted	8.3 A	9.5 A
	Extracted	9.2 A	9.0 A
67 %	Unextracted	7.3 A	6.8 A
	Extracted	7.9 A	6.6 A
50 %	Unextracted	5.8 A	4.8 A
	Extracted	6.1 A	4.7 A
30 %	Unextracted	5.6 A	3.4 A
	Extracted	5.2 A	4.0 A
20.5 %	Unextracted	0.8 A	0.3 A
	Extracted	0.8 A	0.3 A

Table 4.19. Effect of extraction on desorption and adsorption equilibrium moisture content at various level of relative humidity for Ailanthus (*Ailanthus excelsa*)

Relative humidity	Extractive content	Desorption	Adsorption
95 %	Unextracted	20.1 A	30.4 A
	Extracted	22.0 A	28.2 A
80.5 %	Unextracted	13.8 A	11.7 A
	Extracted	12.2 A	11.5 A
75 %	Unextracted	9.8 A	8.7 A
	Extracted	9.7 A	10.0 A
67 %	Unextracted	9.0 A	7.3 A
	Extracted	7.4 A	7.4 A
50 %	Unextracted	6.8 A	5.3 A
	Extracted	6.6 A	5.3 A
30 %	Unextracted	6.2 A	3.9 A
	Extracted	5.6 A	4.5 A
20.5 %	Unextracted	1.3 A	0.8 A
	Extracted	0.9 B	0.5 B

Table 4.20. Effect of extraction on desorption and adsorption equilibrium moisture content at various level of relative humidity for Ushar (*Calotrapis procera*)

Relative humidity	Extractive content	Desorption	Adsorption
95 %	Unextracted	19.0 A	34.2 A
	Extracted	18.4 A	28.7 A
80.5 %	Unextracted	12.2 A	11.0 A
	Extracted	9.3 B	9.5 A
75 %	Unextracted	10.1 A	9.1 A
	Extracted	8.9 A	8.4 A
67 %	Unextracted	8.2 A	6.8 A
	Extracted	7.8 A	6.4 B
50 %	Unextracted	6.0 A	5.0 A
	Extracted	5.7 A	4.7 A
30 %	Unextracted	5.8 A	3.5 A
	Extracted	4.5 A	4.1 A
20.5 %	Unextracted	1.0 A	0.5 A
	Extracted	0.6 A	0.2 A