American-Eurasian J. Agric. & Environ. Sci., 9 (4): 415-421, 2010
ISSN 1818-6769

Physical Characteristics of Coir Pith as a Function of Its Particle Size to Be Used as Soilless Medium

D. Maragatham Jeyaseeli and Samuel Paul Raj

Department of Natural Resources and Waste Recycling, School of Energy, Environment and Natural Resources, Madurai Kamaraj University, Madurai-625 021, Tamil Nadu

Abstract: Coir pith is a mass of heterogeneous particles having diversified physical characteristics. Bulk density was found to be high in small particles (150 μm) and it decreased as particle size increased (2000 μm). High bulk density in smaller particles of coir pith was found to be 0.11 g/cc which is low compared to soil. Total porosity and aeration porosity of the coir pith mass formed of a specific particle size showed direct relationship with particle size whereas water holding porosity had a negative relation. High bulk density showed by big particles had a low total porosity which would cause reduction in growth and distribution of roots of the plants grown on it. Water absorptive and particle size of coir pith showed a strong negative linear correlation. Smaller particles of coir pith which was compactly arranged absorbed more water due to innumerable micro pores than the coarser particles which contained larger but limited amounts of macro pores. Both surface area as well as specific surface area of coir pith particles decreased with the increase in the average size of the coir pith. As water retention in a medium depends primarily on the number and size of the pores and the specific surface area of the medium, it was observed to be higher in the smaller sized particles.

Key words: Coir pith · Bulk density · Surface area · Porosity · Water absorbing capacity

INTRODUCTION

Coconut palm (*Cocos nucifera* L.) is being cultivated in many parts of the world producing around 54 billion coconuts per year from an estimated area of 12.78 million hectare [1]. India produces 22.3 percent of the total coconuts and is being considered as a premier coconut producer in the world. Coconut is known to play a vital role in the economy of many marginal farmers in India [2].

The coconuts are processed in industries to yield oil from dried kernels (copra). The above process generates huge quantities of husk (mesocarp) which was considered to be a waste [3]. These husks are now being utilized as a raw material for the production of coir fiber. During the extraction of coir fibre from the husk, a light weight spongy material is released. This spongy material is referred to as coir pith which accounts for 50-60 percent of the total weight of the husk.

Total generation of coir pith in India is estimated to be around 0.5 million tones per year while the world production is around 3.6 million tones [4]. Therefore coir industries are facing great difficulties in the disposal of coir pith [5]. Very often coir pith is heaped as mounds on way side. Large quantities of coir pith thus stored causes contamination of potable ground water due to the percolation of leachates containing residual phenol from these dumps [6] especially during rainy season. It also acts as an ideal breeding ground for rodents and insect pests [7]. Coir pith is easily blown by wind due to its light weight thereby creating air pollution. In comparison to other waste materials such as saw dust, rice husk and groundnut shell, coir pith is found to have a higher heat value [8,9]. Unfortunately, high levels of carbon dioxide and smoke are released from coir pith while burning due to its poor combustion properties.

To overcome the problems associated with coir pith disposal, many innovative practices are being followed. In certain parts of India, coir pith finds its application in making bricks [5] and particle-boards [10]. A mixture of cow dung and coir pith at 4:1 ratio increases the biogas

Corresponding Author: Dr. D. Maragatham Jeyaseeli, Department of Natural Resources and Waste Recycling, School of Energy, Environment and Natural Resources, Madurai Kamaraj University, Madurai-625 021, Tamil Nadu, India, Tel: +9486504927

production [3]. Coir pith forms a good bedding material in poultry shed [11]. The coir pith bed enriched with poultry litter is directly used as manure for crops such as sorghum, groundnut and sunflower [12]. Removal of fluoride from drinking water is also effected by the application of activated carbon prepared by carbonisation of coir pith [13]. Charcoal made from coir pith is also employed in selected industries to absorb toxic metals (cadmium, arsenic, nickel, copper and lead), harmful dyes (rhodamine B, acid violet and cargo red) and chosen pesticides (paraquet) [14].

Now it is being successfully utilised as a soilless medium for vegetable crops such as bhendi (*Abelmoschus esculentus*) [15], tomato (*Lycopersicon lycopersicum*) [16] and an effective substrate for brinjal (*Solanum melongena*) [17].

Considering the abundant scope of utilizing the coir pith as a major soilless media in many countries especially in terrace gardening for price worthy vegetable crops and also with a great understanding that such soilless media's primary function largely depends on the physical characteristics of the particle involved, this work is initiated.

MATERIALS AND METHODS

Coir pith required for the present study was collected (each per month for a period of one year) from the coir mounds in the vicinity of a coir industry at Solavanthan, Madurai which is about 9 km away from Madurai Kamaraj University where coir processing is being carried out commercially. It was then transported to the laboratory and sun dried for 3-5 days. Subsequently long fibres were removed by hand sorting. As the collected coir pith mass was formed of assorted particles of varied size it was sorted out into different grades (12) based on the particle size using sieves [18]. The occurrence of particular mass was expressed in percent by weight as per the procedure of [19] and followed by [15, 20].

Surface area (SA) of a single particle of a specific grade of coir pith was calculated using the following formula: SA (m^2) = $4\pi r^2$. The surface area of all the particles present in a liter of specific grade of coir pith was calculated as per the procedure of [15]. One liter of coir pith of specific grade was measured in a measuring cylinder and was weighed (w_l). Total number of particles (tn) present in one litre of the coir pith was calculated as tn = (n/0.05 g) x w_l, where n is the number of particles present in 0.05 g of specific grade of coir pith. Surface area of all the particles present in one liter of the coir pith of a specific grade was calculated (SA x tn).

The bulk density (D) of an individual grade of coir pith was assessed as per the procedure of [21]. A clean, dry standard flask of 100 ml (cc) capacity was taken and weighed (w_1). The flask was then filled up to the mark with coir pith of a specific grade and weighed (w_2). The bulk density was D (g/cc) = (w_2-w_1) / 100.

In order to asses the porosity, a plastic cylindrical container of 250 ml capacity was taken. The bottom of the container was pierced with a fine needle so as to have ten holes uniformly distributed at the bottom of it. The holes were then closed with a water proof adhesive tape. Then the container was filled with the coir pith by gently tapping it till the coir pith fills the 250 ml mark. Then water was slowly dripped over the coir pith so that the coir pith was completely drenched and saturated (surface glistens). This process took several hours. The total volume of water added (a) in ml was recorded. Then the container was placed over a water-proof pan and the adhesive tape at the bottom was removed so as to drain the water on the pan. Then the drained water (b in ml) was measured. Total porosity (TP in %) was [(a / 250) x 100]. Similarly the aeration porosity (AP in %) was [(b / 250) x 100]. Water holding porosity (WHP in %) was total porosity (TP in %)-aeration porosity (AP in %).

The water absorption capacity (quantity of water absorbed by a known volume of dry coir pith) was assessed as per the procedure followed by [15, 20]. Sun dried coir pith was used for this experiment.

The experimental set up consisted of a plastic rigid tube of 3 cm inner diameter and 30 cm length. One end of the tube was fixed with nylon net of 50 μm mesh. This set up was clamped in a stand. The dried coir pith was measured (200 ml) in a measuring cylinder accurately by tapping and transferred to the above plastic tube. A burette was also clamped in the stand just above the plastic tube. From the burette a known volume of water (v_1 in ml) was released slowly (drop by drop) to the plastic tube loaded with coir pith. The leachate dripping out from the bottom of the plastic tube was then collected and measured in ml (v_2). From the volume of water dropped into the burette and also from the volume of leachate came out, the actual quantity of water absorbed was calculated. The absorptive (ml / l) was [(v_1-v_2) / 200] x 1000

Water retention capacity of a specific grade of coir pith was estimated for a period of ten days as per the procedure followed by [15, 20]. This enabled to assess the ability of the coir pith to retain the moisture for a specific duration of time and also helped to identify the particle size (grade) which retains maximum moisture in a specific duration of time. A known weight (d in gm) (sun dried) of coir pith in a specific grade was wetted as above, weighed and transferred to a pre-weighed glass tray. The spread thickness of the coir pith in that tray was around 1 cm. It was then kept exposed to air in the laboratory (average temperature 31 °C and average humidity 61 %). After ten days the weight of coir pith in g was noted (Total weight-tray weight) (e). The water retention capacity was [(e-d)/d] x 100 %.

RESULTS

The percentage occurrence by weight of various grades of coir pith (average with one standard deviation) is shown in Fig. 1. The particle size ranging from 475 to 1165 μm occurred above 8.33 percent.

The relation between surface area of all the coir pith particles present in a litre of each specific grade of coir pith and particle size shows that the particle size below 500 μm shows a steep negative relation with the total surface area whereas the relation is feebly negative for the particles above 500 μm size (Fig. 2) ($R^2 = 0.8234$).

The bulk density offered by various grades of coir pith and their relation with particle size is graphically shown in Fig. 3 ($R^2 = 0.9447$). The bulk density and particle size are negatively correlated since the bigger particles are less dense. The total porosity, aeration porosity and water holding porosity of various grades of coir pith in relation to the particle size are shown in Fig. 4. The total porosity and aeration porosity showed a steady increase as the particle size increased. While examining Figs. 3 and 4 together it is known that bulk density and water holding porosity have identical pattern of relationship especially on particle size. The total porosity of the various sized particles has a direct functional relation with aeration porosity. In smaller particles, the total porosity is mainly due to water holding porosity since both the lines are tending to merge in fig. 4. But the role played by water holding porosities in the total porosities diminishes in big particles (Fig. 4).

Total porosity is directly related to aeration porosity whereas water holding porosity is inversely related. In bigger particles, the aeration porosity holds the lion share (Fig. 4). The grade having big sized particles show high aeration porosity and that containing small sized particle size show high water holding porosity. In other words, smaller particles do not hold much aeration and bigger particles do not hold much water.

The role of particle size on the water absorbing capacity of various grades of coir pith is shown in Fig. 5 ($R^2 = 0.9425$). A total of 1015.76 ml of water per litre of coir pith (more than the actual volume of the coir pith) was absorbed by 150 μm particles. The absorption capacity

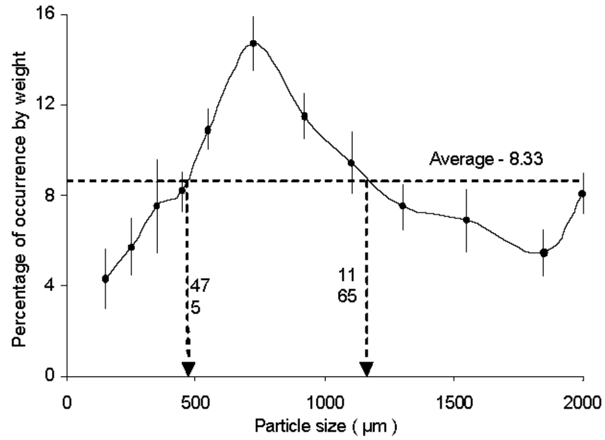

Fig. 1: Particle composition of the coir pith (n=12)

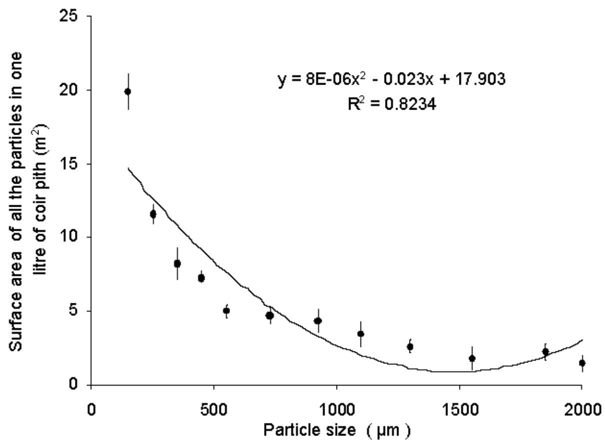

Fig. 2: Relation between surface area of all the particles present in one litre of each grade of coir pith and the corresponding particle size (n=12)

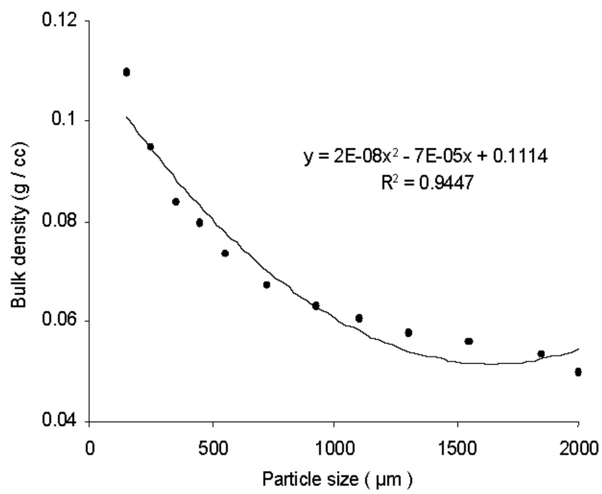

Fig. 3: Relation between the bulk density of each grade of coir pith and the size of the corresponding particle (n = 12)

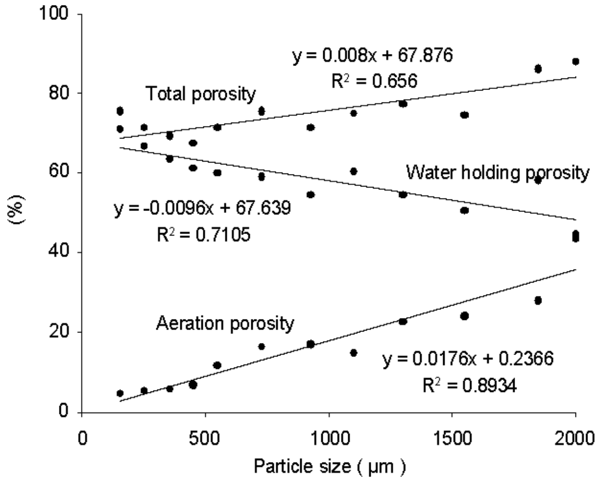

Fig. 4: Relation of the total porosity, aeration porosity and water holding porosity of various grades of coir pith with that of the particle size (n = 12)

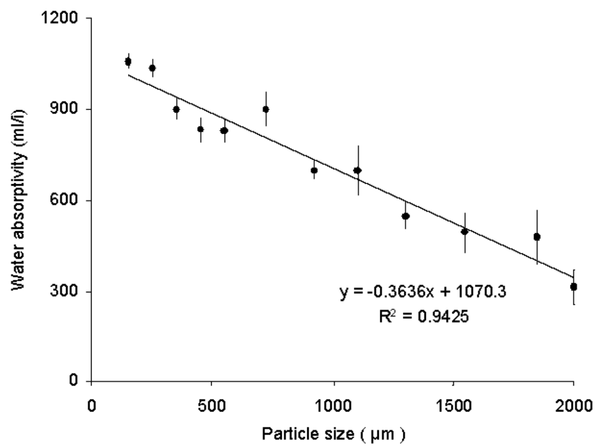

Fig. 5: Water absorptivity in relation to particle size of oir pith (n = 12)

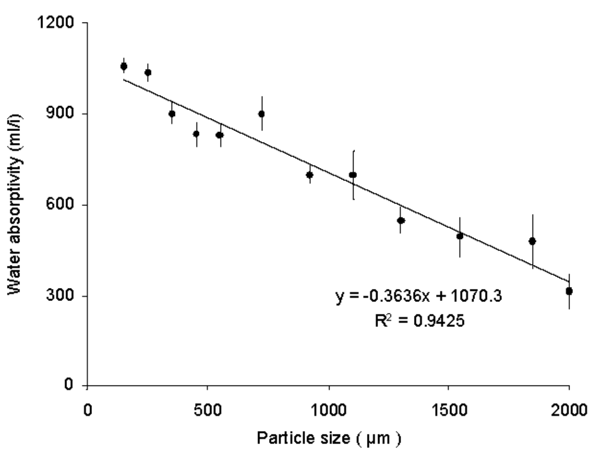

Fig. 6: Water absorptivity in relation to particle size of coir pith (n = 12)

lowered as the particle size of coir pith increased. The 1550 μm particle absorbed 506.72 ml of water per liter of coir pith only. Two fold changes in water absorption were observed for ten fold change in the particle size. The grade of coir pith having the highest particle size (2000 μm) absorbed 343.1 ml per litre of coir pith. Thus the bigger particles neither absorb relatively high quantities of water nor hold water in rich quantities.

Moisture retentivity decreases when the particle size increases. Moisture retention is the function of water holding porosity (Fig. 6). Such water holding porosity is higher in smaller particles (Fig. 4). It means that moisture retention is higher in smaller particles.

DISCUSSION

Coir pith is richly used as soilless media of glass houses. In this context, the particle size of the coir pith is very important. Media developed out of coir pith should provide adequate oxygen, water and nutrients for the proper function of the root. It also should offer physical support to the plants.

The main purpose of studying the particle size distribution by sieve fractionation (Agnew and Leonard, 2003) is to know the particle-wise physical characteristics which has a direct bearing on the functioning [22] of a growing medium.

In the present study, it is observed that the coir pith particles are highly heterogeneous. The percentage occurrences of smaller as well as higher grades of coir pith particles were low when compared to medium grade particles. The coir pith particles ranging from 475 to 1165 μm occurred in higher quantities. [23] in his study reported that medium sized particles occurred in higher percentage in three container substrates (peat mix, bark mix and soil mix). [24] opined that the actual constituent of the medium was not a major factor influencing the rooting response, but the physical properties as well as the management of the substrate were the subject of major importance.

Bulk density is one of the factors determining the successful functioning of a growing medium [22]. The bulk density of coir pith in a filled container is a function of the internal arrangement of the individual particles (Landis, 1990). In the present case, bulk density decreased (0.11 to 0.05 g/cm^3) as particle size of coir pith increased (150 to 2000 μm). According to [25] an ideal growing medium consisting of vermiculite and perlite shall have a bulk density of 0.10 g / cm^3.

The bulk density observed for coir pith [26] was rather high (0.15 g / cm^3). High bulk density is considered to offer mechanical impedence to plants [21]. Any solid medium which provides effective anchorage to the plant roots is to be sufficiently heavy to prevent a potted plant from falling-over due to the weight of the plant [25]. But in the present case the relatively low bulk density has a specific advantage especially when considering this in terrace gardening [15].

The amount of pore space present between particles is expressed in terms of percent porosity and is a function of the size, shape and spatial arrangement of the individual particles of coir pith in the container. Porosity is functionally classified into total porosity, aeration porosity and water-holding porosity [27, 28]. Total porosity is a measure of the total pore space of a growing medium, expressed as the percentage of its volume that is not filled with solid particles. Aeration porosity is a measure of that part of the total pore space that is filled with air after the growing medium is saturated with water and then allowed to drain freely. The pores that contain air are relatively lame and are termed as macro pores. Water holding porosity is the measure of the part of the total pore space that remains filled with water after the growing medium is saturated with water and allowed to drain freely. The pores that contain water are relatively small and are termed as micro pores. Porosity is important to the horticultural properties of a growing medium, since it influences the moisture-holding and nutrient-holding properties.

According to [29] well-formulated growing media contain about 60-80 percent total porosity. [29] stated that the total porosity of a growing medium should be more than 50 percent. In the present study, total porosity of fine (150 μm) to coarser particle (2000 μm) ranged between 75.6 and 88.2 percent. Regarding aeration porosity [30] recommended maintenance of aeration porosity of approximately 25 to 35 percent for container tree seedlings. In the present case, aeration porosity of various grades of coir pith ranged from 4.6 to 43.7 percent. A well formulated growing medium is expected to contain a mixture of macro pores for aeration and drainage and micro pores for water-holding ability.

In container nurseries, porosity is determined mainly by the range of particle size present in the growing medium [29]. Large particles do not pack as closely as small particles and therefore will have high total porosity as in the case of present work. Aeration porosity and water-holding porosity of coir pith have a peculiar relationship. When the size of the coir pith particle increased, the water-holding porosity decreased which ultimately increased the aeration porosity.

Porosity and bulk density of soilless medium were strongly linked. The increase in bulk density reduced the porosity of the medium which ultimately hamper the growth and distribution of roots of the plants grown in it.

In the present study, the bulk density decreased with the increase in coir pith particle size. Total porosity and aeration porosity increased along with the increase in particle size. In comparison with bulk density, total porosity and aeration porosity decreased as bulk density increased which was confirmed by [31]. The aeration porosity is inversely related to the bulk density.

[32] reported reduced soil water availability under increased bulk density. The quantum of total pore space (TPS) in a root medium is inversely proportional to the bulk density [33]. As the bulk density decreases, total pore space increases linearly. It is also confirmed that the increased bulk density to the root zone provides less pore space for water movement, adversely affecting the crop growth by limiting root growth [34, 35].

[36] reported that the total porosity was about 96 percent and that the materials' air-filled porosity was 22-40 percent depending upon the length of time the material had been composted. Apparently these readings are on a mass of coir pith not specific to any particle. [37] observed the bulk density, total porosity, water-holding porosity and aeration porosity of coir pith as 0.08 g / cm^3, 95, 79 and 16 percent respectively.

Aeration is necessary for the diffusion of CO_2 away from the roots. Therefore growing medium is required to be sufficiently porous to avoid the accumulation of CO_2 at the root zone, otherwise that would lead to the suffocation and eventual death of plant roots. Lack of aeration caused by poor drainage leads to a wet, waterlogged condition that is a conducive condition for the development of diseases like devastating root rots.

Water absorptive and particle size of coir pith showed a strong negative linear correlation ($y = -0.3636x + 1070.3$). Smaller particle which was compactly arranged absorbed more water due to the innumerable micro pores than the coarser particles which contained larger but limited amounts of macro pores.

Total surface area of all the particles present in a unit volume decreased with the increase in the average size of the coir pith. As the surface area of various grades of coir pith increased, water absorptivity of coir pith also increased. Besides being absorbed water is also held on the surface of these particles as a film, the total amount of water in the medium increased as the particle diameter decreased [25].

Aeration porosity was found increasing when the particle size of coir pith increased. But there is a parallel decrease in the moisture retentivity. Aeration and water-holding capacity (moisture retention) are the properties of primary interest to any agriculturist because they directly affect plant growth. Micro pores present in lower grades of coir pith resist the water to move out which in turn increases the moisture retentivity. Moreover a reduction of the particle size leads to a decrease in aeration and might also possibly decrease the water availability [38].

There is a strong correlation between the presence of finer particles in the mix and aeration porosity. A significant negative correlation is also found between aeration porosity and water holding capacity which varied from 585 to 740 cm^3 / dm^3. Substrates with very high porosities are likely to restrict the lateral movement of water and nutrients, whereas substrates with low aeration porosities are likely to result in reduced root densities, due to a lack of aeration and perhaps encourage the incidence of soil-borne pathogens [39]. Inadequate drainage and poor aeration in container media are the major limiting factors in the production of quality nursery crops. In the present study, due to less aeration and high water holding capacity in the smaller grade of coir pith, root length of the plants may be minimized. Increase in porosity of a substrate helps to suppress pathogenic infestations but a reduction in water holding capacity may induce water stress in plants.

Water retention in a medium depends primarily on the number and size-distribution of pores and the specific surface area of the medium [40-43]. [44] reported that 80 percent of the observed variations in the percentage increase in water retention were due to the texture of the medium. Excessive large pores however decrease the amount of water the media can store [45].

REFERENCES

1. Mathew, M.T., 2004. Coconut industry in India: An overview. Indian Cocon. J., 35(7): 3-29.
2. Reddy, S.L. and P.K. Thampan, 1988. Commercial exploitation of coconut husk in Orissa. Indian Cocon. J., 19(3): 3-5.
3. Mathew, A.C., T.V. Singh and S.J.D. Bosco, 2000. Technology to produce biogas from coir pith. Indian Cocon. J., 31(3): 46-48.
4. Pillai, C.K.S., P.K. Rahatgi and K. Gopakumar, 1981. Coconut as a resource for materials and energy in the future. J. Sci. Ind. Res., 40: 154-165.
5. Dan, T.K., 1993. Development of light weight building bricks using coconut pith. Indian Cocon. J., 23(11): 12-19.
6. Gopal, M. and A. Gupta, 2001. Coir waste for a scientific cause. Indian Cocon. J., 31(12): 3-15.
7. Grimwood, B.E., 1975. Coconut palm products. Food and Agriculture organization of the United Nations, Rome, pp: 142.
8. Krishnan, R., 1990. Pyrolysis and combustion characteristics of saw dust, rice husks, groundnut shell and coir dust using gas chromatography. Trop. Sci., 30: 223-228.
9. Sudhira, H.S. and A. Jacob, 2000. Reuse of by-products in coir industry: A case study. Dept. of Environmental Engg. Sri. Jayachamarajendra college of Engg. Mysore, Karnataka, India. Proc. Internet conference on Material Flow Analysis of Integrated Bio systems. (Mar-Oct 2000). Available at wesite. http:// www.ias.unu.edu/proceedings/icibs/ic-mfa/jacob/paper.html.
10. Viswanathan, R., 1998. A process for the production of particle board from coconut pith. Indian Cocon. J., 29(7): 5-7.
11. Maheswarappa, H.P., R. Dhanapal, C.C. Bidappa and V.T. George, 2000. Coir pith-its use in poultry farm. Indian Cocon. J., 30(9): 1-2.
12. Savithri, P., S. Subbiah, R. Nagarajan, S. Mani and A. Gopalswamy, 1991. Effect of composted coir pith and gypsum applications on soil properties and yield of rice in sodic soil. In: Proceedings of seminar on "Utilization of coir pith in Agriculture". 20th Nov., Tamil Nadu Agricultural University, Coimbatore, India, pp: 129-135.
13. Dahiya, S. and A. Kaur, 1999. Studies on removal of fluoride by coconut coir pith carbon. Indian J. Environ. Protection, 19(11): 811-814.
14. Anonymous., 1999. Coir pith waste for removing dyes, toxic metals from waste water. Indian Cocon. J., 30(2): 3.
15. Ross, P.R., 2002. Studies on coir pith as an artificial soil medium. Ph.D., Thesis, Madurai Kamaraj University, Madurai, India.
16. Ramalakshmi, D., 2005. Studies on coir pith as a soilless medium to tomato plant. M.Sc., thesis., Madurai Kamaraj University, Madurai, India.
17. Ramaswamy, K., R. Nagarajan and T.S. Manickam, 1985. Manurial value of coir pith, Madras Agriculture J., 72: 533-535.

18. Agnew, J.M. and J.J. Leonard, 2003. The physical properties of compost. Comp. Sci. Util., 11: 238-264.
19. Brady, C.N., 1996. The nature and properties of soils, 10^{th} ed., Prentice-Hall of Indian Pvt. Ltd., Connaught circle, New Delhi.
20. Edsor, C., 2005. Performance of chosen earthworm species on the vermicomposting of coir pith. Ph.D., thesis, Madurai Kamaraj University, Madurai, India.
21. Sinha, A.K., S.K. Bandyopadhyay and T.K. Sarkar, 1998. Soil mechanical impedence in relation to crop growth In: Theory and practice in agrophysics measurements. (Ed. Pub: Gupta R.P. and Ghildyal, B. P.) A-104, Maya puri, Phase IV, New Delhi.
22. Richard, M.P., 2006. Effect of nursery media particle size distribution on container-grown woody ornamental production. M.Sc., thesis. B. S., Louisiana state University.
23. Drzal, M.S., W.C. Fonteno and D.K. Cassel, 1999. Pore fraction analysis: A new tool for substrate testing. Proc. Int. Sym. Growing Media and Hydrophonics. Ed. A. P. Papadopoulos. Acta Hort., 181. ISHS., pp: 43-53.
24. Reisch, K.W., 1967. Rooting media. Proc. Intl. Plant Prop. Soc., 117: 356-361.
25. Nelson, P.V., 1985. Greenhouse operation and management. 3^{rd} ed., Prentice-hall, Inc., Englewood Cliffs, New Jersey, 07632, pp: 598.
26. Idiculla, R., L.G. Radhika, S.K. Seshadri and K.G. Satyanarayana, 1983. Microstructure and water sorption mechanism of coconut pith. J. Chem. Tech. Biotech., 33(A): 439-445.
27. Handreck, K.A. and N.D. Black, 1984. Growing media for ornamental plants and turf. Kensington, New South Wales university press, Australia, pp: 401.
28. Bethke, C.L., 1986. Systematic approach solves grower problems. Greenhouse Manager, 4(11): 171-177.
29. Havis, J.R. and W.W. Hamilton, 1976. Physical properties of container media. J. Arboric., 2(7): 139-140.
30. Whitcomb, C.E., 1988. Plant production in containers. Stillwater, OK: Lacebark Publications.
31. Khan, A.R., 2002. Mulching effects on soil physical properties and peanut production. Ital. J. Agron., 6(2): 113-118.
32. Hillel, D., 1971. Soil and water. Physical principles and processes. Academic press, New York.
33. Bunt, A.C., 1983. Physical properties on mixtures of peats and minerals of different particle size and bulk density for potting substrates. Acta Hort., 150: 143-153.
34. Khan, A.R., 1996. Influence of tillage on soil aeration. J. Agron. Crop Sci., 178: 73-78.
35. Khan, A.R., D. Chandra., S.S. Quraishi and R.K. Sinha, 2000. Soil aeration under different soil surface conditions. J. Agron. Crop Sci., 185: 105-112.
36. Verdonck, O., 1983. Reviewing and evaluation of new materials used as substrates. In: Symposium on substrates in horticulture other than soils in situ, Acta Horticulture 150. International Society for Horticultural Sciences, Commission Plant Substrates, The Hague, The Netherlands, pp: 467-489.
37. Evans, R., 1998. The development and properties of container soils-Making a good mix. Growing Points, Dept. of Environmental Horticulture, University of California, Davis. Winter, 2(1): 1-6.
38. Gruda, N. and W.H. Schnitzler, 2004. Suitability of wood fiber substrate for production of vegetable transplants-I. Physical properties of wood fiber substrates. Scientia Horticulturae, 100: 309-322.
39. Cox, J.D.L. and I.E. Smith, 1997. The interaction of air-filled porosity and irrigation regime on the growth of three woody perennial (Citrus) species in pine bark substrates. SNA research conference. 1000, Johnson Ferry Road, Suite-130, Marietta, GA-30068-2100, 42: 169-174.
40. Childs, E.C., 1940. The use of soil moisture characteristics in soil studies. Soil Science, 50: 239-252.
41. Danielson, R.E. and P.L. Sutherland, 1986. Porosity, In: Methods of soil analysis, Part I. Rev. Physical and Mineralogical Methods. (Ed.) A. Klute. Amer. Soc. of Agron. Monogr, 9: 443-460.
42. Milks, R.R., W.C. Fonteno and R.A. Larson, 1989. Hydrology of horticultural substrates: I. characteristics of horticultural container media. J. Amer. Soc. Hort. Sci., 114(1): 48-52.
43. Sharma, P.K. and L. Bhushan, 2001. Interpretation of effect of organic matter on soil-water retention. J. Indian Society of Soil Sci, 49(3): 494-95.
44. Khaleel, R., K.R. Reddy and M.R. Overcash, 1981. Changes in soil physical properties due to organic waste applications: A rewiew. J. Environ. Qual, 10(2): 133-141.
45. Hensley, D. and J. Yogi, 1997. Substitutions for peat in Hawaii nursery production. Horticulture Research Note. Horticulture Research Note (HRN-11), College of Tropical Agriculture and Human Resources (CTAHR), University of Hawaii at Manoa.