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ARTICLE

Optimization of Organic Mulches Thickness Improves Soil Moisture Retention under Controlled Conditions

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ABSTRACT

Organic mulch can improve the moisture, chemical composition, dust, and dust suppression of soil, and beautify the environment. In view of the rapid evaporation rate and serious loss of soil water in tropical areas, this paper explored the effect of organic mulch materials with different thickness on the increase of soil water retention rate and the improvement of soil water loss caused by evaporation. Rubberwood sawdust (RWS), rubberwood bark (RWB), coconut fiber (CF), and Mulch (MC) were selected as the mulching materials. Field experiment and laboratory experiment were performed, and soil-moisture content and temperature were continuously monitored. However, from the daily measurement of water content at constant conditions (29°C ± 0.2°C, 74% ± 1% air RH) in the laboratory experiment, the results of variance analysis (ANOVA) showed that there was no significant difference between the soil-water content of covered samples and bare soil ($P > 0.05$). In the field experiments, the analysis of variance indicated significant differences in the soil-moisture content owing to the effect of the covering material ($P < 0.01$). Mulching increased the soil-moisture content with smaller fluctuations in the deep soil compared with bare soil. The most stable soil-moisture content were achieved by RWS, RWB, CF, and MC, with thicknesses of 5, 3, 7, and 5 cm, respectively, compared with bare soil, and the average water contents of the 0–40 cm soil layer was 0.58%, 0.01%, 0.82%, and 0.93%, respectively. Vertically, the intensity of the change in soil moisture decreased gradually with increasing depth, and was more stable than that of bare soil and other treatments. Among them, the difference in water content between the adjacent gradient soil layers (the soil layers are graded every 10 cm in depth) M_{3-7} (0.011 ± 0.004) was the smallest. It can be concluded that CF mulching materials with a thickness of 7 cm would be preferable when selecting mulching materials for controlling soil moisture in tropical cities.

KEYWORDS

Organic mulch; soil moisture content; humid tropical region; soil improvement

1 Introduction

Soil moisture reflects the dry and wet conditions of soil and is an important parameter of the land-air cycle. It is also key for studying hydrological processes, such as rainfall infiltration, runoff formation, plant transpiration, and soil evaporation [1–3]. A low soil moisture content not only restricts the utilization of water by roots and microorganisms and affects their activity [4,5], but also indirectly inhibits soil respiration due to the decrease in the availability of organic substrates for microbial respiration [6]. If the soil moisture content is relatively low for a long time, a dry soil layer will form [7], and grassland and ground-cover plants will wither and even die across large areas due to long-term water shortages, with land desertification becoming increasingly severe. However, when the soil moisture content exceeds the capacity of the field, the high soil saturation or water state will lead to weakened soil permeability, limit the O_2 circulation required for root and microbial respiration, significantly decrease the CO_2 diffusion rate of soil respiration metabolism [8], and restrict soil respiration. The plant growth status will also respond to changes in the soil water supply intensity, which will directly affect plant metabolism, and the damage to plants caused by water deficit or over-saturation greatly exceeds the sum of all other stress factors [9]. If the soil moisture content is maintained at a balanced and stable level, the content of soil nutrients can be better improved to promote the growth and development of plants, thereby increasing the total biomass (Fig. 1) [10,11]. Therefore, controlling the soil water content to maintain it in equilibrium for a long time plays a crucial role in the soil structure characteristics, microbial activity, and seed germination. Additionally, soil moisture is a decisive factor in the effects and benefits of urban landscaping.

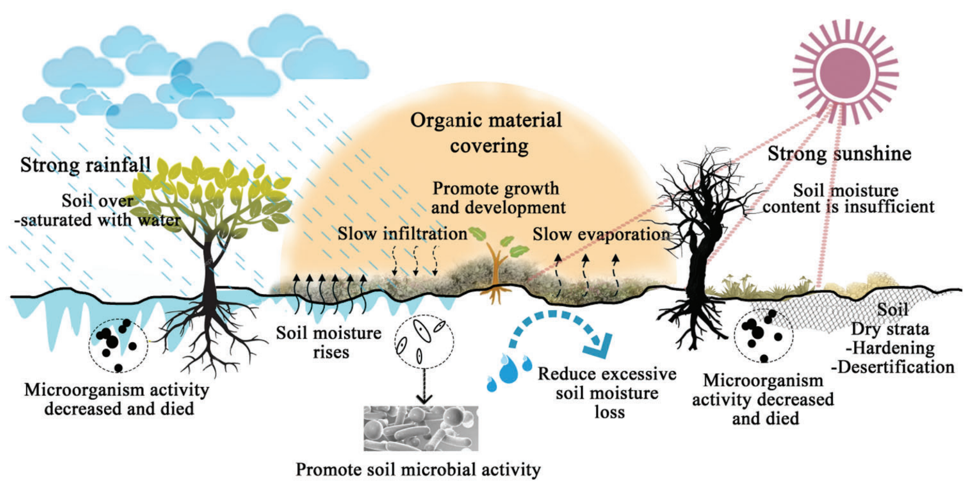

Figure 1: Principles and conceptual framework of the effect of organic mulch under extreme soil moisture contents

Currently, mulching and chemical water-saving methods are used to increase the soil water content and slow water loss. Mulching water-saving methods use materials such as straw mulch, plastic mulch, sand, and so on, while chemical water-saving methods use materials such as water-retaining agents, drought-resistant agents, and anti-transpiration inhibitors to improve the soil and maintain its water-soil balance. In practice, plastic mulch induced ecological problems, while green degradable mulching film is more expensive. The spraying of reagents and application of sand and gravel will slowly affect the soil structure and properties, and negatively affect plant growth. Organic mulch, such as straw, is simple and fast to use, and not only produces large amounts of nutrients after decomposition, but also reduces the loss of and maintains soil moisture. The use of organic mulch also recycles waste biomass resources [12] and effectively improves the added value of forestry by-products by returning the residues or urban greening waste from forestry production to urban green spaces through processing.

Several researchers have investigated the effects of organic mulching in terms of soil-water availability [8]. Zribi et al. [13] evaluated the effectiveness of different organic and inorganic covering materials on evaporation control in laboratory experiments. Conflicting effects of mulching on soil moisture and temperature have been reported owing to different climatic conditions (e.g., rainfall and temperature), mulching material types, soil-energy behavior, soil characteristics, and crop types [14,15]. In hot weather, high soil temperatures increase evaporation, which reduces soil moisture [16]. In addition, the optimum soil temperature for botany growth under mulching can be effective for safe water use and higher crop yield. However, the effects of straw mulching have been studied extensively [17,18]. Inorganic mulch, such as pebbles and ceramics, can significantly increase soil-water content in the short term, but long-term use of mulch can cause soil compaction and increase soil bulk density, and organic mulch can reduce rainwater alluviation and improve soil porosity [19]. Currently, Pinus tabuliformis Carr., Pinus bungeana Zucc, Ailanthus altissima, Robinia pseudoacacia L., and other garden wastes growing in northeastern and central China are the most commonly used types of organic mulch in China. However, few studies have explored the utilization of tropical garden waste, which may improve the soil of urban green spaces when used as an organic covering material. In tropical areas, rubber and coconut provide sustainable utilization of resources, but also cause a large number of rubber wood (Hevea brasiliensis) and coconut trees (Cocos nucifera) leftover materials, sawdust and other waste, failed to release the full value of trees, causing outstanding problems for environmental protection and resource utilization. The rational utilization of the surplus resources of rubberwood and coconut is very important. Therefore, field experiments and laboratory experiments were performed to investigate garden waste from tropical areas used as organic mulching materials (Rubberwood sawdust-RWS, rubberwood bark-RWB, coconut fiber-CF, and Mulch-MC) to cover rubber forest soil in Danzhou City, Hainan Province. The effects of the different types of organic mulch of varying thicknesses (3, 5, 7 cm) on the stability of soil-water content and the vertical horizontal distribution law were explored using a fitting equation for soil-water content and time change and by calculating the coefficient of variation (Cv) for soil vertical distribution. The results are expected to provide a theoretical basis for soil improvement and restoration in tropical areas and the organic mulch species with the best soil-moisture regulation effect and the most suitable laying thickness was selected from tropical garden wastes.

2 Materials and Methods

2.1 Test Site

The experimental site is located in Experimental Building No. 5 of Danzhou Campus, Hainan University (19°30′52.49″ N, 109°29′56.01″ E). Hainan experiences a humid tropical monsoon climate, with hot summers, warm and humid winters, and abundant sunshine throughout the year. The average annual rainfall and temperature are 1815 mm and 23.5°C, respectively.

2.2 Test Materials

(1) Mulch (MC) is a new kind of energy-saving and environmental protection Mulch product, which is processed by pulverizing, fermenting, dyeing and grading the organic matter remaining from landscaping and tree cutting as raw materials. The main components of MC are brown fir (*Cunninghamia lanceolata*) chippings with a bark size of 3–5 cm, purchased from the Organic Ecological Mulch Company.

(2) Agricultural and forestry wastes consisting of rubberwood and coconut trees. These materials were processed into rubberwood sawdust (RWS), rubberwood bark (RWB), and coconut fiber (CF). RWS originated from rubberwood industry shavings, RWB consisted of the dried and peeled bark of

rubberwood, and the CF originated from the coconut-coat fiber, which was artificially torn and pruned from the coating on the outside of coconut shells. The Mulch (MC) purchased was the covering with the widest market circulation (Fig. 2).

Figure 2: Images of the RWS (A), RWB (B), CF (C), and MC (D)

2.3 Small-Scale Experiments

Experimental treatments were analyzed to determine the saturated water content of soil, using an 8 cm × 12 cm (internal diameter × height) beaker. Different soil saturated water content was measured at constant conditions (29°C ± 0.2°C, 74% ± 1% air RH) and normal ventilation laboratory conditions. The soil samples with a height of approximately 4 cm were added to the beaker, and water was added until supersaturated occurred (where the soil surface retains water precipitation after standing for 20 min). The experimental treatments were put into a constant temperature drying oven at 105°C, and the samples were weighed after 6 h. The soil saturated water content was determined by a small-scale experiment and the difference is small under different conditions, which verified the limit of soil-water content preservation, provided a reference basis for subsequent experiments.

Four experimental treatments were performed to compare the loss of water by evaporation from wet soil with and without a mulch cover under a constant condition (29°C ± 0.2°C, 74% ± 1% air RH) and normal ventilation laboratory conditions. A preliminary experiment was conducted on a small scale and over a short span to observe the possible effect of mulch, using 8 cm × 12 cm (internal diameter × height) beaker. During the experiment, soil samples were added into glass beakers to a height of approximately 5 cm, and water was added until the soil was saturated. Organic mulch with a thickness of approximately 4 cm was added to two of the experimental treatments, and the four experimental treatments were put into a constant temperature drying oven at 30°C. The weight was compared after 12 h. The small-scale samples helped us to understand the process by which organic mulch retains soil water and to verify that organic mulch can mitigate soil water loss under different experimental conditions.

2.4 Control Experiments

The laboratory experiment was performed in a climatic chamber at constant conditions (29°C ± 0.2°C, 74% ± 1% air RH) at Danzhou Campus of Hainan University for 10 days. The temperature and humidity were controlled by a powerful humidifier. The hourly temperature and humidity changes were measured using a hygrometer to simulate the average temperature and humidity of Danzhou City in Hainan Province in July. The field experiment was conducted at the Danzhou Campus Laboratory of Hainan University for 10 days with normal ventilation and direct sunlight for more than 6 h per day.

The two experiments, on a larger scale and over a longer time, used 35 cm × 45 cm (internal diameter × height) plastic columns with saturated water content of soil. The soil employed in all experiments was air-dried and sieved (<2 mm). It was a sandy loam (tending toward sandy clay loam; 64.3% sand, 17.2% silt, and 19.1% clay) obtained from the rubber plantation test field in Danzhou City. In the experiments, the bulk density of the packed soil was 1350 kg·m^{-3} (Cv = 5.73%) and its porosity was 42.7%; no mechanical forces were applied to the soil, other than gravity. The soils in the containers were irrigated with distilled water oversaturation (9719.69 ± 362.18 mL). The soil was then left to settle naturally for 48 h, and its surface was repaired and leveled for mulching. To explore the effects of different mulch type and thicknesses, 3-, 5-, and 7-cm layers of RWS, RWB, CF, and MC were added to the soil barrels; the absence of mulch coverage was used as the control. The barrels with these treatments were labeled $M_{1–3}$, $M_{1–5}$, $M_{1–7}$, $M_{2–3}$, $M_{2–5}$, $M_{2–7}$, $M_{3–3}$, $M_{3–5}$, $M_{3–7}$, $M_{4–3,}$ $M_{4–5}$, $M_{4–7}$, and CK, respectively. Each organic mulch treatment was repeated twice. For all sample sizes, there were two situations: soil, and soil + organic material covering. The experiments were monitored just after the organic material covering was applied.

2.5 Soil Water Content and Coefficient of Variation Estimation

Soil water content monitoring in vertical direction can reflect the water cycle in soil and the influence of organic mulch on soil water content in different layers. The mass water content was measured by manual sampling and drying. Soil samples were collected at 08:00 daily at depths of 10, 20, 30, and 40 cm, for measurement with a geotome diameter of 3.2 cm, an inner diameter of 2.6 cm and a length of 50 cm, which were labeled as S10, S20, S30, and S40, respectively. Immediately after soil extraction, insert a plastic PVC pipe with a diameter of 3.2 cm into the hole left after soil extraction, so as to help isolate the contact area between the deep soil of the columnar hole and the air, and close the opening of the PVC pipe with tape on the upper end to avoid secondary air circulation. Each depth was sampled twice. The soil sample should not be less than 50 g. Put the soil sample into the self-zip plastic bags and weigh them within 3 h to prevent water loss.

$$SWC = (M_1 - M_2)/M_2 \times 100 \tag{1}$$

where SWC is the soil water content (%), M_1 is the fresh soil weight (g), and M_2 is the dry soil weight (g).

The degree of variation in the SWC was expressed by the Cv.

$$C_V = \sigma^2/X \tag{2}$$

where C_V is the coefficient of variation of soil moisture, σ^2 is the standard deviation of SWC determination for the sample, and X is the average SWC of the sample.

2.6 Data Processing

Excel software was used for data processing, while SPSS 25.0 was used to test the significance of the corresponding data by a one-way ANOVA, and Origin 2019 was used to analyze and plot the fitting equation.

3 Results

3.1 Effect of Organic Mulch Thickness on the Average Soil Water Content in the Laboratory Experiment

During the laboratory experiment, the one-way ANOVA test applied to the variable relative water loss showed there was no significant difference between each treatment and CK ($P > 0.05$). Additionally, the mulching thickness was not the main factor affecting the water content of organic mulch under laboratory conditions (Table 1). With a constant temperature and humidity, the SWC was mainly determined by the structural properties of the covering materials, such as the particle size, porosity, and arrangement. The moisture contents of treatments $M_{2–7}$, $M_{3–3}$, $M_{3–5}$, $M_{4–5}$, and $M_{4–7}$ were higher than that of CK, 26.08%, 25.66%, 25.75%, 25.96% and 25.87%, which was mainly due to the separation of heat and water exchange between soil and the atmosphere by the covering materials. At a high external temperature, the water evaporation intensity was high and the covering materials had a certain water holding capacity, which effectively suppressed soil water evaporation. Additionally, the diffusion of water molecules due to the internal movement of the soil improved the soil water content of different layers, causing the average water content to increase. Thus, the rubberwood bark (RWB), coconut fiber (CF), and mulch covering (MC) favoured water retention in the soil, as do most other common organic mulches [13,20,21]. The water content under the different RWB thicknesses decreased in the following order: $M_{2–7} > CK > M_{2–5} > M_{2–3}$. There was no significant difference between each treatment and CK; however, there was a significant difference between the 7 and 3-cm mulching treatments ($P < 0.05$), and the difference in the average water content was 1.53%. With the same particle size structure, the pore density of different mulch thicknesses varied. The larger the thickness, the higher the saturated water content, and the greater the improvement in the SWC. But, interestingly, the soil moisture content of rubberwood sawdust (RWS), CF and MC increased firstly and then decreased with the increase of mulch thickness, in which RWS increased by 0.7% and decreased by 0.98%. CF increased by 0.09% and decreased by 0.47%; MC increased by 0.42% and decreased by 0.09%, which is a trait directly linked with another important quality of the mulches: their lifetime [22].

Table 1: Average effects of different organic mulch thicknesses on the SWC in the laboratory experiment

Treatment	SWC(%)	Treatment	SWC(%)
$M_{1–3}$	24.59 ± 0.93a	$M_{3–3}$	25.66 ± 1.1a
$M_{1–5}$	25.29 ± 1.56a	$M_{3–5}$	25.75 ± 0.69a
$M_{1–7}$	24.31 ± 1.46a	$M_{3–7}$	25.28 ± 0.96a
CK	25.55 ± 0.5a	CK	25.55 ± 0.5a
Treatment	SWC(%)	Treatment	SWC(%)
$M_{2–3}$	24.55 ± 1.18b	$M_{4–3}$	25.54 ± 0.92a
$M_{2–5}$	25.45 ± 1.24ab	$M_{4–5}$	25.96 ± 0.58a
$M_{2–7}$	26.08 ± 0.8a	$M_{4–7}$	25.87 ± 0.51a
CK	25.55 ± 0.5ab	CK	25.55 ± 0.5a

Note: Different lowercase letters indicate significant differences at $P < 0.05$.

3.2 Effect of Organic Mulch Thickness on the Diurnal Variation in the Soil Water Content

3.2.1 Effect of RWS Thickness on Soil Water Content

The air temperature and humidity were considered in the field experiment stage (Fig. 3). The changes in the water contents of soil covered by RWS wood chip layers with different thicknesses included median, upper quartile, lower quartile, minimum, maximum, and outlier values. The dashed line in Fig. 4A represents an extreme SWC. The results showed that the bare SWC was the lowest, with a low median value and fluctuation from low to high, with the lowest average SWC of 21.7%. The soil moisture fluctuation range in the mulching treatments was small, the data distribution was more concentrated, and there was no abnormal value. The SWC of $M_{1–5}$ was higher than that of the other thicknesses, with the highest median and similar average values (25.11%), and then $M_{1–7}$ (24.93%) and $M_{1–3}$ (23.96%). The air temperature and humidity fluctuated unimodally and the SWC fluctuated, but did not significantly change (Fig. 3), this is different from what Wang et al. [23] found, their study suggests that soil moisture content has a significant negative correlation with air temperature. This experiment indicating that the structure and particle size of RWS significantly contributed to regulating the SWC, the main reason is that rubber wood sawdust particles are smaller, bulk density is larger, and lignocellulose degradation rate is high [24]. The change in the soil moisture difference before and after 10 d of mulching decreased in the following order: CK (5.61%) > $M_{1–3}$ (1.95%) > $M_{1–7}$ (1.93%) > $M_{1–5}$ (0.58%). The results indicated that soil surface mulching could regulate the SWC and stabilize the soil water activity, with the stabilization decreasing in the following order: $M_{1–5} > M_{1–7} > M_{1–3}$.

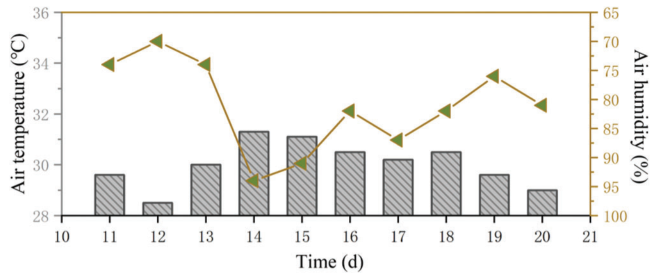

Figure 3: Temperature and humidity in July 2020

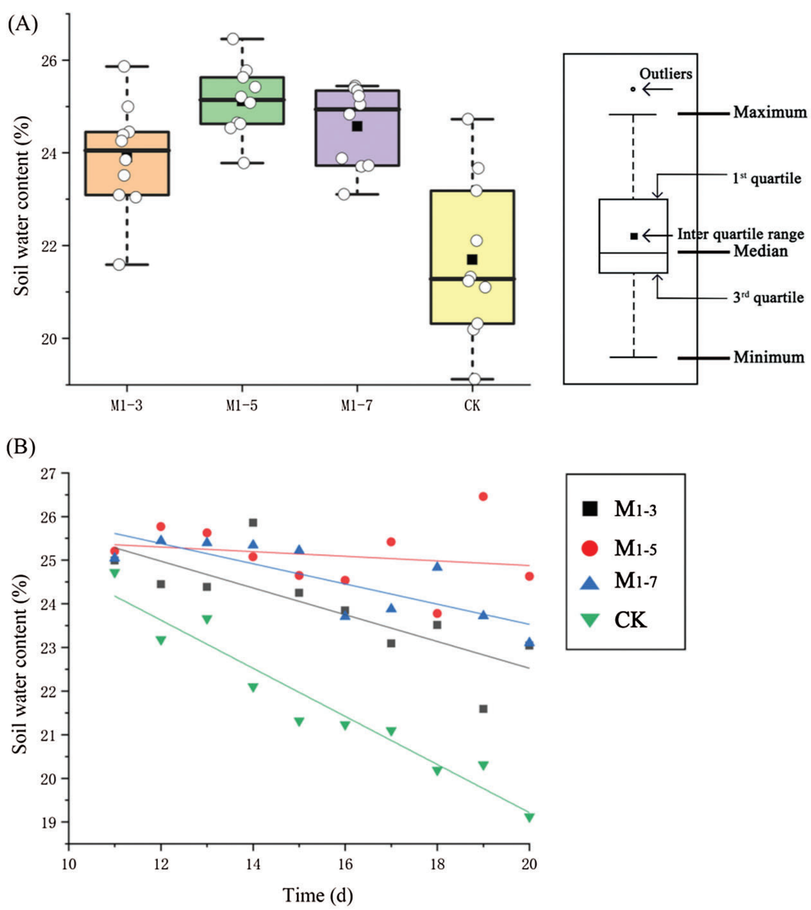

Figure 4: Average daily moisture content of the 0 to 40-cm soil layer in the 3, 5, and 7-cm rubberwood sawdust (RWS) treatments (A); Linear equation fitting of the SWC and time under different rubberwood sawdust (RWS) thicknesses (B)

The relationship between the SWC and time for different RWS thicknesses was fitted, and the results showed that the diurnal variation in the water content and time had a high determination coefficient, and decreased in the following order: CK (0.93106) > M_{1-5} (0.84478) > M_{1-7} (0.64631) > M_{1-3} (0.56972). The fitting regression equation values of group M_{1-3} were relatively low (Fig. 4B, Table 2). The values of parameter a for M_{1-3}, M_{1-5}, M_{1-7}, and CK were all negative, indicating that the diurnal change intensity of soil moisture gradually decreased with time, and parameter a decreased in the following order: M_{1-5} (−0.053) > M_{1-7} (−0.231) > M_{1-3} (−0. 307) > CK (−0.551). The range of soil moisture regulation decreased over time and tended to gradually stabilize. The 5-cm RWS mulch treatment notably affected the SWC. According to the significance analysis, the SWC of each treatment was as follows: 25.11 ± 0.76% (M_{1-5}), 24.57 ± 0.87% (M_{1-7}), 23.9 ± 1.18% (M_{1-3}), and 21.7 ± 1.73% (CK). There was a statistically significant difference between the RWS thicknesses ($F = 15.731$, $P < 0.05$), and the results indicate that a 5-cm RWS layer had the best effect on water control. This is consistent with the results of Chen et al. [25]: organic mulch with a thickness of 5-cm had the most detailed effect on soil moisture content within the range of 10-cm.

Table 2: Fitting equations of the SWCs and time under different mulch thicknesses

Treatment	Fitting equation (y = ax + b)	R^2
M_{1-3}	y = −0.30677x + 28.65773	0.56972
M_{1-5}	y = −0.05299x + 25.93574	0.84478
M_{1-7}	y = −0.23149x + 28.15799	0.64631
M_{2-3}	y = −0.1811x + 26.58942	0.29064
M_{2-5}	y = −0.41201x + 30.18885	0.58179
M_{2-7}	y = −0.29611x + 27.57286	0.45331
M_{3-3}	y = −0.16797x + 25.88552	0.82962
M_{3-5}	y = −0.24957x + 27.78262	0.52332
M_{3-7}	y = −0.15031x + 26.77372	0.69715
M_{4-3}	y = −0.39825x + 29.3967	0.7158
M_{4-5}	y = −0.33255x + 29.0398	0.69084
M_{4-7}	y = −0. 49025x + 31.51253	0.89825
CK	y = −0.55137x + 30.24259	0.93106

Note: y is the soil moisture content (%); x is time (d); a is the change rate of the SWC; b is the fitted initial soil moisture content (%); and R^2 is the determination coefficient.

3.2.2 Effect of RWB Thickness on the Soil Moisture Content

The daily variation in the SWC under different rubberwood bark (RWB) thicknesses is presented in (Fig. 5A). The soil moisture content of M_{2-5} (23.91%) greatly differed to that of CK. The daily moisture content range was 4.9%, indicating that the influence of the 5-cm RWB layer on the SWC was extremely unstable due to the suitable pore size for the movement of water molecules, increase in soil moisture activity, and other factors [26]. The SWCs of M_{2-3} and M_{2-7} were not greatly different. The distribution of soil moisture was more uniform under the 3-cm treatment, and the average value was 23.86%. The absolute change order of the difference in the soil moisture content before and after 10 d of coverage was as follows: CK (5.61%) > M_{2-5} (3.42%) > M_{2-7} (1.67%) > M_{2-3} (0.01%). The results indicated that RWB mulching could increase the soil water availability and stabilize the soil water activity, with the stability decreasing in the following order: $M_{2-3} > M_{2-7} > M_{2-5}$.

The determination coefficients of the fitting equation results of the SWC and time for the RWB treatments with different thicknesses all exceeded 0, and the fitting was valid (Fig. 5B, Table 2). The variation rate of water content A could be obtained by the derivative of soil moisture content Y with respect to mulch time X, and the value of parameter A decreased in the following order: M_{2-3} (−0.181) > M_{2-7} (−0.296) > M_{2-5} (−0.412) > CK (−0.551). That is, there were abundant secondary metabolites in the bark of rubber tree, and the bark corkification was serious [27]. In addition, the four means were significantly different from each other (Tukey method), the level with the thinnest hydromulch having the highest value. Thus, a RWB layer with a thickness of 3 cm had the best effect on soil and water conservation. This is consistent with Zhang et al. [28]. study on the structural characteristics of rubber tree bark, whose results show that rubber bark has a low hardness and high wood density, the thinner the material, the more conducive to soil moisture regulation.

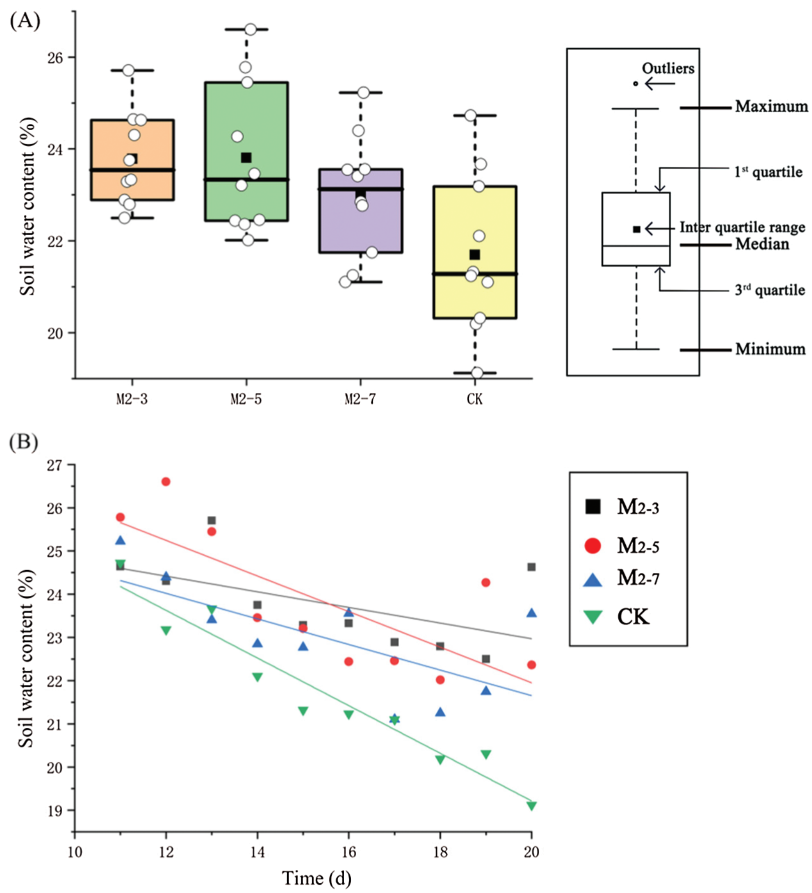

Figure 5: Average daily SWCs in the 0 to 40-cm layer under the rubberwood bark (RWB) treatments with thicknesses of 3, 5, and 7 cm (A); Linear equation fitting image of soil water content and time under different rubberwood bark (RWB) thicknesses (B)

3.2.3 Effect of CF Thickness on the Soil Moisture Content

Among the different treatments, the SWC of $M_{3\text{–}7}$ was highest (26.58%), while the moisture content of $M_{3\text{–}5}$ was more evenly distributed, and the median was closer to the average value of 23.91% (Fig. 6A). The treatment with coconut fiber (CF) layers of 5 and 7 cm achieved excellent results. The results indicated that 5 and 7-cm layers of CF mulch physically blocked the exchange between the soil water and atmosphere, directly affected the soil capillary transport path of water molecules, and changed the circulation of the soil-air-water system, thus forming a new internal soil water circulation system which according to Qu et al. [29] has a significant impact on surface energy balance. The absolute change in the SWC before and after 10 d of coverage decreased in the following order: CK (5.61%) > $M_{3\text{–}3}$ (3.39%) > $M_{3\text{–}5}$ (1.07%) > $M_{3\text{–}7}$ (0.82%). The results indicated that using CF as a mulching material could balance the SWC well, and the stability decreased in the following order: $M_{3\text{–}7} > M_{3\text{–}5} > M_{3\text{–}3}$.

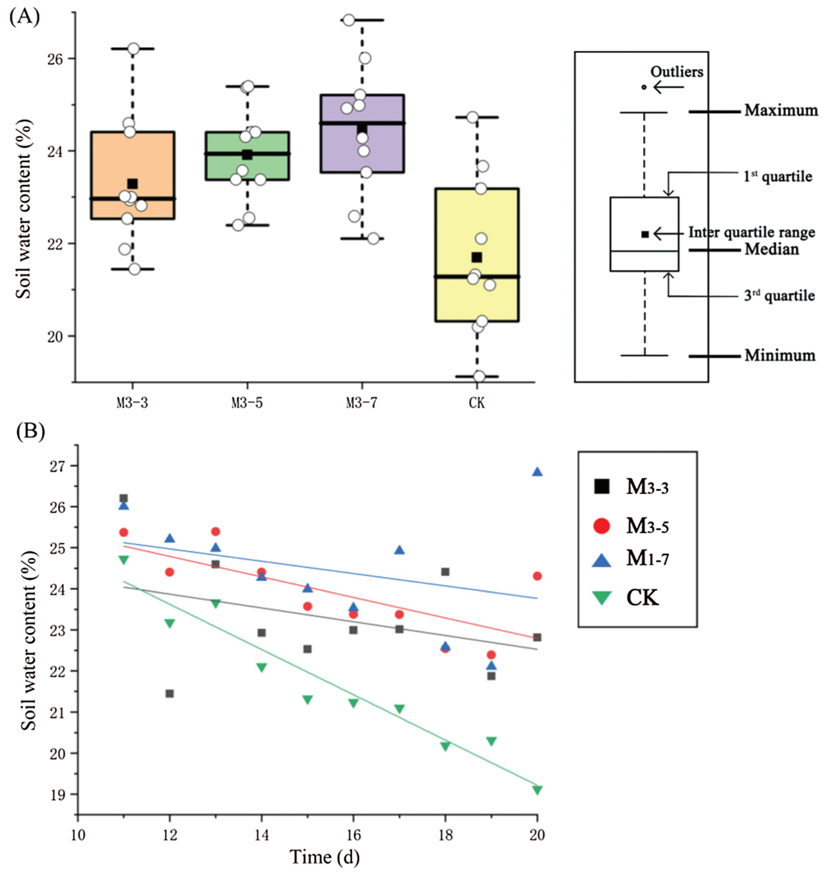

Figure 6: Average daily SWC in the 0 to 40-cm soil layer under coconut fiber (CF) layers with thicknesses of 3, 5, and 7 cm (A); Linear equation fitting of the SWC and time under different coconut fiber (CF) layer thicknesses (B)

The relationship between the SWC and time for the CF treatment with different thicknesses was fitted, and the results showed that the determination coefficient was high, with parameter a decreasing in the following order: $M_{3–7}$ (−0.15) > $M_{3–3}$ (−0.168) > $M_{3–5}$ (−0.249) > CK (−0.551) (Fig. 6B, Table 2). When parameter A is negative, the intensity of the change in the SWC under CF cover with a thickness of 7 cm gradually weakened over time, the evaporation rate slowed, and a constant influence range was maintained at the earliest time. This is consistent with the experimental results of Liang et al. [30–32]. CF has good moisture retention and storage characteristics, and can resist decomposition better than ordinary plant fibers, material thickness is positively correlated with the effect. In conclusion, CF mulching with a thickness of 7 cm had the best effect on soil moisture.

3.2.4 Effect of MC Thickness on the Soil Moisture Content

The maximum mean SWC under different Mulch (MC) thicknesses (Fig. 7A) was 23.86% for $M_{4–7}$; however, the degree of data dispersion was relatively large. Soil moisture content was higher than bare soil, similar to our findings, Ginovart et al. [33] observed that the use of mulch resulted in significant retention of moisture near the surface of soil, where water availability played avital role in crop productivity. The median of $M_{4–5}$ was close to the average water content (23.22%) and slightly lower than that of $M_{4–7}$; however, the values were uniformly distributed with strong stability. The relationship between the SWC and time was fitted under different MC thicknesses, and the determination coefficient values were all high. Parameter a decreased in the following order: M_{4-5} (−0.332) > M_{4-3} (−0.398) > M_{4-7} (−0.491) > CK (−0.551) (Fig. 7B, Table 2). Organic mulch is mostly composed of Chinese fir sawdust, and Chinese fir itself has a high moisture content, soft material and long fiber [34,35], so too thick material is not conducive to the regulation of soil water content. The 5-cm MC layer could control the soil water activity to a greater and more stable extent. However, its slope was lower than that of treatments M_1, M_2, and M_3; therefore, the ability of MC to regulate soil water was weaker than that of the other treatments. According to the significance analysis, the SWCs of the treatments with MC mulching at different thicknesses were as follows: 23.89 ± 1.21% (M_{4-7}), 23.22 ± 1.42% (M_{4-5}), 22.91 ± 1.57% (M_{4-3}), 21.7 ± 1.73% (CK), F = 4.828, ANOVA shows that $P < 0.05$. In conclusion, the effect of the 5-cm MC layer on soil moisture regulation was better.

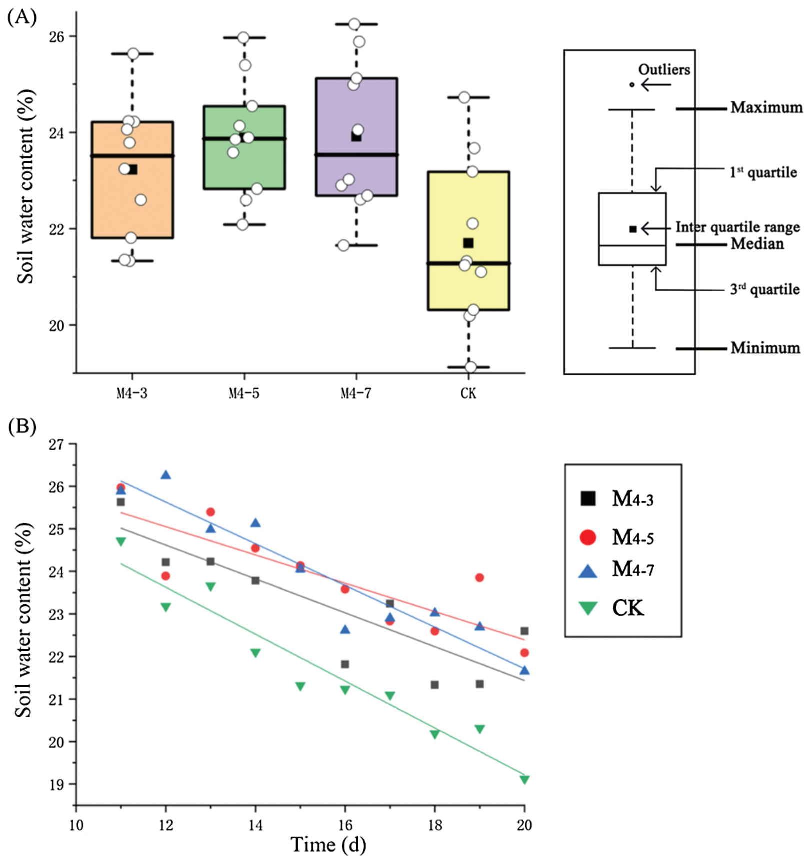

Figure 7: Average daily water content in the 0 to 40-cm soil layer under Mulch (MC) at thicknesses of 3, 5, and 7 cm (A); Linear equation fitting of the SWC and time under different Mulch (MC) thicknesses (B)

3.2.5 Vertical Variations in Soil Moisture under Mulching

The coefficients of variation for the SWC were obtained using Eq. (2). By comparing the SWCs of mulch treatment and CK for each group, it was found that the change in the moisture content of the 0–40 cm soil layer in CK was the most dramatic (0.092 ± 0.013). The difference in the coefficient of variation between adjacent soil layers of M_{1-5}, M_{2-3}, M_{3-7}, and M_{4-5} is 0.018 ± 0.004, 0.023 ± 0.007, 0.011 ± 0.004, and 0.038 ± 0.012, respectively. From this, we know that, compared with bare soil, the soil moisture content in different layers of the treated soil was more stable. At 10–20, 20–30, and 30–40 cm, as the soil depth increased, the variation coefficient of soil-water content for M_{1-5}, M_{2-3}, M_{3-5}, M_{3-7}, and

M_{3-5} followed a downward trend, while the change in the other treatments fluctuated, indicating that the intensity of soil-water content change of these five treatments in deep soil gradually decreased; the soil-water content tends to be stable, but the water content of deep soils is very unstable, which was mainly due to the barrier effect of mulching materials that caused water in the upper soil layer to evaporate slowly and dissipate into the air. The deep soil moisture was attributed to the slow capillary movement of water to the upper soil layer. Severe fluctuations in the SWC were mainly concentrated in the 20 to 30-cm layer, and the soil moisture followed a similar trend with depth between the organic material mulching and bare soil treatments. The fluctuations in the variation coefficient indicated that the vertical variation in soil moisture was dramatic and the variation coefficient of the bottom layer generally increased sharply, indicating that the vertical and horizontal regulation of the SWC by spreading of mulching materials was unstable. The capillary force generated by the soil was larger due to the smaller particle size and finer capillaries of the soil used in this experiment, which strengthened the upward transport of soil capillary water and caused the formation of a larger vertical trend of SWC change. In conclusion, 5, 3, 7, and 5-cm layers of RES, RWB, CF, and MC had a more significant effect on controlling the vertical balance of the SWC. The vertical variation coefficient of the SWC in M_{1-5}, M_{2-3}, M_{3-5}, M_{3-7}, and M_{4-5} indicated that the difference between the adjacent soil layers of M_{3-7} was small (0.011 ± 0.004), and that they were the most stable and balanced (Table 3). Therefore, CF mulching with a thickness of 7 cm had the most significant effect on the vertical distribution of soil water, and was suitable for mulching a large area to improve the water content of different soil layers. This is consistent with the results of Zhang et al. [36]: Under the cover of the CF, the soil exhibited relatively high moisture content at different depths. This is attributable to the following factors: on the one hand, the CF physically blocks sunshine and wind, reducing the evaporation of soil moisture; on the other hand, the cold and hot airs meet inside the CF, making it easy for soil moisture to condense into water droplets.

4 Discussion

As a new type of ecologically and environmentally sustainable mulching material, organic mulch has many ecological and economic benefits, and has a significant impact on the SWC [37]. Spreading of mulching materials can effectively improve the SWC, but thicker layers are more desirable; the results showed that an organic mulch thickness of 2–10 cm was most appropriate [38]. If the mulching thickness was insufficient, the outward movement of soil-water molecules will be intensified, more water will undergo evapotranspiration, which will not aid water retention. If the covering thickness is excessive, the covering material will absorb a large amount of water, rendering it difficult for water to penetrate the soil's surface, and increasing the cost of soil conservation [39]. Most of the published research only examines the effect of 2–10 cm mulch thickness on soil-moisture content from an empirical perspective, there are relatively few quantitative comparison and scientific and reasonable analysis from the perspective of mathematical statistical analysis. Therefore, different types of covering materials with thicknesses of 3, 5, and 7 cm were explored in this study. The SWC was tested daily, and the coverage thickness of each material that achieved the most stable water retention was selected for the analysis of the vertical and horizontal changes in the SWC to determine the optimal organic mulching material thickness for water conservation. Chen et al. [40] demonstrated that organic mulch significantly promoted soil-water retention, whereas Chen et al. [41] explored the utilization of garden waste at thicknesses of 3, 6, and 9 cm, and their results demonstrated that 6 cm exerted beneficial effects on water retention, soil temperature regulation, soil nutrient improvement, and weed suppression, similar to the results of this study.

Table 3: Comparison of vertical variation coefficients of soil moisture between different types of Mulch with varying thicknesses and bare soil

Soil depth (cm)	$M_{1–3}$	$M_{1–5}$	$M_{1–7}$	CK
0–10	0.033451	0.052341	0.033878	0.095324
10–20	0.083512	0.092843	0.083733	0.180712
20–30	0.03316	0.078326	0.046005	0.096767
30–40	0.13445	0.05926	0.036951	0.258946
Soil depth (cm)	$M_{2–3}$	$M_{2–5}$	$M_{2–7}$	CK
0–10	0.038474	0.05938	0.033878	0.095324
10–20	0.068491	0.07839	0.079861	0.180712
20–30	0.053257	0.044436	0.046146	0.096767
30–40	0.029886	0.149247	0.072335	0.258946
Soil depth (cm)	$M_{3–3}$	$M_{3–5}$	$M_{3–7}$	CK
0–10	0.077293	0.064714	0.074815	0.095324
10–20	0.10199	0.076969	0.087349	0.180712
20–30	0.060014	0.072293	0.072626	0.096767
30–40	0.084381	0.049123	0.061031	0.258946
Soil depth (cm)	$M_{4–3}$	$M_{4–5}$	$M_{4–7}$	CK
0–10	0.069876	0.09058	0.060022	0.095324
10–20	0.113368	0.14081	0.093927	0.180712
20–30	0.060228	0.123346	0.080477	0.096767
30–40	0.077299	0.08506	0.073838	0.258946

In field experiments, the average daily water content of soil with different thicknesses of organic mulch (Figs. 4A–7A) indicated that the data were evenly distributed among four quartiles. The results showed that the SWC was less affected by the external temperature and humidity when organic mulching materials were used. Because of Hainan's unique tropical monsoon climate, it is hot and humid all year round. When the air temperature was very high, the temperature difference between the covered soil and air was increased greatly, resulting in a lower soil temperature than air temperature and a slower soil-water evaporation rate; this is consistent with results of Que [42]. Additionally, organic mulch first acted as a barrier to internal water evaporation, ensuring a high SWC. When the air humidity was very high, the organic mulch could absorb water from the air more easily and supplement the soil. When the humidity was close to the saturated vapor pressure, soil-moisture evaporation decreased rapidly, increasing the SWC [43]. This is consistent with the results of Shumova [44] which showed that in humid areas, when the soil is covered with grain straw, evapotranspiration decreases, which may cause some disturbance to the natural structure of the hydrological cycle and may lead to excessive soil wetting. Through daily SWC analysis, it is concluded that rubber wood sawdust with 5 cm thickness and rubber wood bark with 3 cm thickness had the best effect on soil-water retention; this was attributed to the molecular structure of rubber wood. The BET analysis of rubber wood showed that further increases in the decomposition process increased the amount of volatile organic compounds and created more pores, increasing the surface area. The higher surface area is preferable because it helps to improve the soil structure and increases the total water retention in the soil [45]. In this study, it was found that 7 cm thick coconut fiber caused the most obvious improvement effect on soil-moisture content, this was supported by the FTIR analysis of coconut fiber, which showed that the fiber contained a large amount of -OH and had strong polarity, water absorption, and moisture absorption [46].

By comparing the vertical distribution of the SWC, it was found that, when the upper soil moisture was infiltrated due to gravity, the SWC followed a decreasing trend. When the soil moisture evaporated upward or the capillary water rose, the moisture content of the underlying soil tended to increase. The layer of mulching materials physically blocked the evaporation of water vapor from the soil, and the large temperature difference between the morning and evening caused the water vapor to condense and form droplets that returned to the soil, resulting in internal surface soil-water circulation [47]. This phenomenon would be further aggravated with increases in the temperature difference or humidity. The size and morphology, pore structure, water retention, and other natural characteristics of plant fibers play an important role throughout the physical cycle. The results show that 5-cm rubberwood sawdust, 3-cm rubberwood bark, 7-cm coconut fiber and 5-cm Mulch have large effects on vertical and horizontal SWC; 7-cm coconut fiber had the most balanced effect on adjacent soil layers, which was beneficial to the growth of plants with deep and shallow roots [31].

The findings that differ in this study were the decomposed matrix particle size (CF) water effect of the covering material, the better the cover material properties, and the closer the covering material to the matrix of the soil, plant fiber capillary channels, and soil capillary pore diameter. This improves the ability to establish a continuous channel for water molecules, facilitating frequent exchange of water molecules. This is consistent with the research results of Shi [48]. The fiber structure of the mulching material with a large particle size (RWB) was too close and large pores were present between the particles, which increased the soil-water activity and thereby affected the soil-water balance.

5 Conclusion

By observing the changes in soil moisture under different types of mulch with different thicknesses, the following conclusions can be preliminarily drawn:

(1) The daily average variation in soil-water content showed that rubberwood sawdust (RWS), rubberwood bark (RWB), coconut fiber (CF), and Mulch (MC) layers with thicknesses of 5, 3, 7, and 5 cm, respectively, had a significant regulatory effect on the SWC balance.
(2) The results of soil vertical water content showed that the soil covered with a 7-cm layer of coconut fiber exhibited the greatest stability in the vertical water content distribution, with a clear effect on SWC control observed.
(3) The results of the comprehensive evaluation showed that 7-cm thick coconut fiber mulching material had a better effect on soil-moisture content.

The above results provide a reference for the selection of OGC materials suitable for urban greening. However, the selection must also consider local conditions, as different regions vary in solar radiation, rainfall features, soil type, and plant type.

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