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Bionomical Observations of Small Carpenter Bee, *Ceratina smaragdula* Fabricius (Hymenoptera: Apidae)

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Abstract

The small carpenter bee, *Ceratina smaragdula* Fabricius is a non-*Apis* pollinator of many economically important crops. The nesting biology, nesting preferences, architecture, foraging, hibernation, and mating behavior of this solitary bee were investigated. Fifteen nests of *C. smaragdula* collected during summer from three nesting locations (roadsides, field sides, and near houses) were examined for the targeted attributes. *C. smaragdula* highly preferred (66.67%) field sides for nesting at a mean height of 82.74 cm from the soil surface. The nesting preference of *C. smaragdula* along roadsides and houses was 26.67% and 6.67%, respectively. The Ravenna grass (*Saccharum ravennae*) was highly preferred (66.67%) nesting material, followed by Wheat (*Triticum aestivum*) stored straw (20.00%), and common Reed (*Phragmites australis*) was the least preferred (13.33%) for nest building. *C. smaragdula* hibernated from early October to February, broke hibernation in the first week of March, and initiated mating immediately. The main reproductive period was from March to August, and the first generation emerged from late April to early May. The peak insect population was recorded from June to August. The period of foraging was from March to September. The mean nest length, nest diameter, and nest entrance diameter were 11.15 cm, 0.79 cm, and 0.53 mm, respectively. *C. smaragdula* preferred a single gallery containing 3-5 cells/gallery. Each gallery contains eggs, larvae, pupae, and adults. The development period of a generation was 4-5 weeks, with 3-4 generations per year. *C. smaragdula* started foraging early in the morning (7.27 am) and ceased in the afternoon (4.71 pm). The mean time foraging per flower was 21.67 seconds, and the bees returned to the nest after 7.48 min of their first forage. These findings might help design the artificial nesting needed to preserve *C. smaragdula*.

Introduction

The carpenter bees (Hymenoptera: Apidae) are categorized into two leading families: small and large. The small carpenter bees belonging to the Tribe *Ceratini* have a wide-spread bee fauna (Udayakumar & Shivalingaswamy, 2019), with small body sizes ranging from 2.2-12.5 mm (Michener, 2007). *Ceratina smaragdula* Fabricius, 1787, is a small carpenter bee belonging to the subfamily Xylocopinae (Hymenoptera; Xylocopinae: Apidae). These bees are hairless and darkly metallic green to black. The Xylocopinae subfamily comprises 350 species and is characterized by yellow facial markings

(Hirashima, 1969; Michener, 2007). *C. smaragdula* bees are distributed worldwide and are commonly found in South Asia (van der Vecht, 1952; Hirashima, 1969). These bees have also been found in the Hawaiian Islands and are mainly introduced for pollination purposes (Daly et al., 1971). *C. smaragdula* are commonly regarded as solitary bees (Michener, 2007).

C. smaragdula bees are abundant in nature, and their females prefer to build linear nests in dead twigs (Guedot, 2004; Michener, 2007). Female bees construct the nest, select the twig, chew with mandibles, and make tunnels. The nest construction typically requires approximately a week to complete. To provide the nest with nutrients, the female collects the pollen to form mass provision to lay eggs on it. The female scraps the pith (delicate plant stem tissues) to cover the egg-laying/brood cells. Typically, the female also uses the pith to create cell walls between each developing offspring (Rehan et al., 2009). Female bees spend their entire generative period in a single nest. After completing oviposition, the bees protect their nest from predators and parasites (Guedot, 2004; Lucia et al., 2015; Ali et al., 2016; Ali et al., 2017). *C. smaragdula* bees are polylectic, and their linear nests make them ideal for studying social interaction and intra-nest behavior (Rehan et al., 2009). Various factors, such as weather and chemical pesticides, directly affect several insects' life cycles and seasonal activities, including bees (Desneux et al., 2007). Voltinism (generations per year) in carpenter bees is vulnerable to environmental conditions and the availability of food (Gerling et al., 1989; Numata & Shintani, 2023).

C. smaragdula bees play a significant role in the pollination of many flowering plants, including alfalfa, weeds, bitter guards, and other crops (Kapil & Kumar, 1969; Wyatt & Sandra, 2017). Solitary and non-*Apis* bees are equally crucial as *Apis* bees during pollination of indigenous plant species (Hongjamrassilp & Warrit, 2014; Ali et al., 2017). These bees feed on the nectar of visited plants and have a crucial role in pollination (Batra, 1976). There are approximately 263 species of bees in Pakistan, which provides us with the basics of the biology of nesting and foraging in *C. smaragdula* (Ascher & Rasmussen, 2010; Ali et al., 2016). Considering the importance of *C. smaragdula* in pollination, the present research was conducted to study the bionomics, nesting preferences, hibernation, reproduction, pollination, nest architecture, nest biology, and foraging of these bees.

Material and Methods

Study location

The study was conducted in different locations in the Swabi district of Khyber Pakhtunkhwa Province, Pakistan. The main cultivatable crops in the targeted area were the canola, sunflower, alfalfa, and Egyptian clover (Ali et al., 2017). In this region, the climate was humid, with heavy rains during summer with relative humidity (RH) of > 60%. The range of temperature (minimum-maximum) and RH were 01-42 °C and 30-40%, respectively. *C. smaragdula* is an abundant pollinator of the cultivated crops in the northwestern region of Pakistan and a potential candidate for the study of nesting biology and foraging activities (Ali et al., 2016).

Nesting preference and activities of small carpenter bee

The nests of *C. smaragdula* were randomly collected from three nesting sites: roadsides, field sides, and near houses during summer. These nesting sites were discovered during the quick survey and sampling of bees, and the percent nesting preferences for nesting locations and materials were calculated. The bee activities such as hibernation, first mating, nest initiation (first generation), reproduction period, preparation of hibernation, awaking from hibernation, peak population, and pollination services (foraging: outgoing and incoming foragers) were monitored throughout the year during 2018-19 on a weekly basis. The bees were considered to be emerging from hibernation at their first appearance, and mating activities were noted during the flowering stage. The exploration of bees for nests in different nesting materials was marked as the nest initiation period, and random nests were dissected at different intervals to check the development of the first generation. The period of nesting and mating observation was noted as the reproduction period. The period of foraging was noted from March to September, which ceased in October. When no bee was seen during late October, it was considered the start of hibernation.

Foraging of *C. smaragdula*

Prior to nest sampling, different foraging characteristics such as foraging starting time, return time after first forage, incoming bees with pollen load, time of foraging on flowers, and cessation of foraging were recorded from fifteen nests of *C. smaragdula*. The visitation of *C. smaragdula* on different fruit species, cucurbit family flowers, ornamental flowers, wildflowers, and weeds was also monitored. The visitation data on different flower types during the foraging season (March–September) was collected every week from early morning until late evening. The starting and ending times of foraging were also monitored,

Sampling of nests

Fifteen nests of *C. smaragdula* were collected in the evening after the return of foraging bees. The nests entrances were closed with adhesive tape. Various nest features, such as the height of the nests (distance) from the soil surface, branch length, length of the nest, branch diameter, nest diameter, and diameter of the entrance, were measured. Afterward, the collected nests were stored in a refrigerator for 24 hours to sacrifice the insects. After gentle dissection, the composition of each nest (number of galleries, number of cells per gallery, and length of cell) and content of galleries (number of eggs, larvae, pupae, and pollen) were recorded.

Data analysis

The nest measurement data were recorded in centimeters (cm) and millimeters (mm). Simple descriptive statistics in Excel were used to calculate the mean and standard error from the foraging and nest measurement data.

Results

The results revealed the measurements of nests, nest composition, foraging activities, and nesting preference of *C. smaragdula*. The series of nests and entrances of *C. smaragdula* at various locations (near the housing area and field area) are shown in Figure 1. Figure 2 illustrates the longitudinal section of the nest and displays information regarding different life stages, the number of cells in each nest, and the variation in cell length.

Nesting preferences

The nesting preferences and nesting materials of *C. smaragdula* at different locations are presented in Table 1. *C. smaragdula* highly preferred (66.67%) the area near field sides for nest building, followed by roadsides (26.67%) and near houses (6.67%). Furthermore, Ravenna grass (*Saccharum ravennae*) was a highly preferred nesting material (66.67%) by *C. smaragdula* to make their nests. Some nests were also built with stored straws of Wheat (*Triticum aestivum*) and common Reed (*Phragmites australis*) with preference values of 20.00% and 13.33%, respectively (Table 1).

Fig 1. Nests of *Ceratina smaragdula* (a) near a housing area (b) nest entrance on a field side.

Fig 2. Longitudinal section of *Ceratina smaragdula* nest (a) different life stages (b) brood cells with larvae and adults.

Table 1. Nesting preferences of *Ceratina smaragdula* at different locations and nesting materials.

	Testing attribute	Number of nests	Nesting Preference
Nesting locations	Field sides	10	66.67 %
	Roadsides	4	26.67%
	Near houses	1	6.67%
Nesting materials	Ravenna grass (*Saccharum ravennae*)	10	66.67%
	Wheat (*Triticum aestivum*) stored straw	3	20.00%
	Common Reed (*Phragmites australis*)	2	13.33%

Activities of *C. smaragdula*

Our data suggested that *C. smaragdula* was in hibernation from October to February. It awoke from hibernation in the first week of March and subsequently started mating during March. After mid-March, they started nesting in dry wood. The main reproduction period was noted from March to August. The first generation emerged in late April or early May. The peak population was recorded from June to August. The bees were found to pollinate crops, wild plants, and weeds from March to September. The bees initiated their preparation for hibernation during September. No bee was seen during late October and was taken as the start of the hibernation period (Table 2).

Table 2. Annual activity calendar of *Ceratina smaragdula.*

Activities	Months											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Hibernation	+	+	–	–	–	–	–	–	–	+	+	+
Awaking from hibernation	–	–	+	–	–	–	–	–	–	–	–	–
1st mating	–	–	+	–	–	–	–	–	–	–	–	–
1st generation	–	–	–	+	+	–	–	–	–	–	–	–
Reproduction Period	–	–	+	+	+	+	+	+	–	–	–	–
Preparation of hibernation	–	–	–	–	–	–	–	–	+	–	–	–
Peak population	–	–	–	–	–	+	+	+	–	–	–	–
Pollination services	–	–	+	+	+	+	+	+	+	–	–	–

+ shows the availability of a specific activity of *C. smaragdula* over the year.

Nest measurements

The mean distance of nests above the soil surface was 82.74 ± 20.19 cm. The mean length of branches containing the nests was 14.58 ± 1.37 cm, and the nest length was 11.15 ± 1.14 cm. The branch diameter, nest diameter, and nest entrance were 1.11 ± 0.13 cm, 0.79 ± 0.12 cm, and 0.53 ± 0.08 mm, respectively (Fig 3 and Table S1). In some nests, the entrance was blocked by the metasoma of a female. No parasitized or diseased nests were found during the study period. The measurement of each tested nest's architecture is presented in Table S1.

Composition of nest and life cycle of *C. smaragdula*

The average number of galleries per nest was 1.00 ± 0.00 with 3-5 cells/gallery. The average number of cells per nest was 4.13 ± 0.74, and the cell length was 8.44 ± 1.48 mm. Some empty cells were also recorded in the nests. The nest's cells contained eggs, larvae, and pupae. The eggs were whitish and laid on a pollen mass. After hatching, the larvae have a creamy yellowish color and feed on pollen mass. The pollen mass was enough to sustain the larvae until pupation (Figure 2). The mean numbers of eggs, larvae, and pupae per nest were 0.93 ± 0.80, 1.0 ± 0.76, 1.13 ± 0.83 and 1.80 ± 0.86, respectively. The development period was from 4-5 weeks, and 3-4 generations per year were recorded (Fig 3 and Table S2).

Foraging

C. smaragdula has a wide range of foraging. The bees preferred to visit flowers of the cucurbit family, ornamental flowers, wildflowers, and weeds, especially *Parthenium*. The bees also visited different fruit species such as citrus and *Ziziphus* spp. The foraging started early in the morning at 7.27 ± 0.23 am and ceased in the afternoon at 4.71 ± 0.35 pm. The bees returned to the nest after 7.48 ± 0.41 min of their first forage. *C. smaragdula* spent an average of 21.67 ± 8.67 seconds per flower during forging on different flowers (Fig 3 and Table S3).

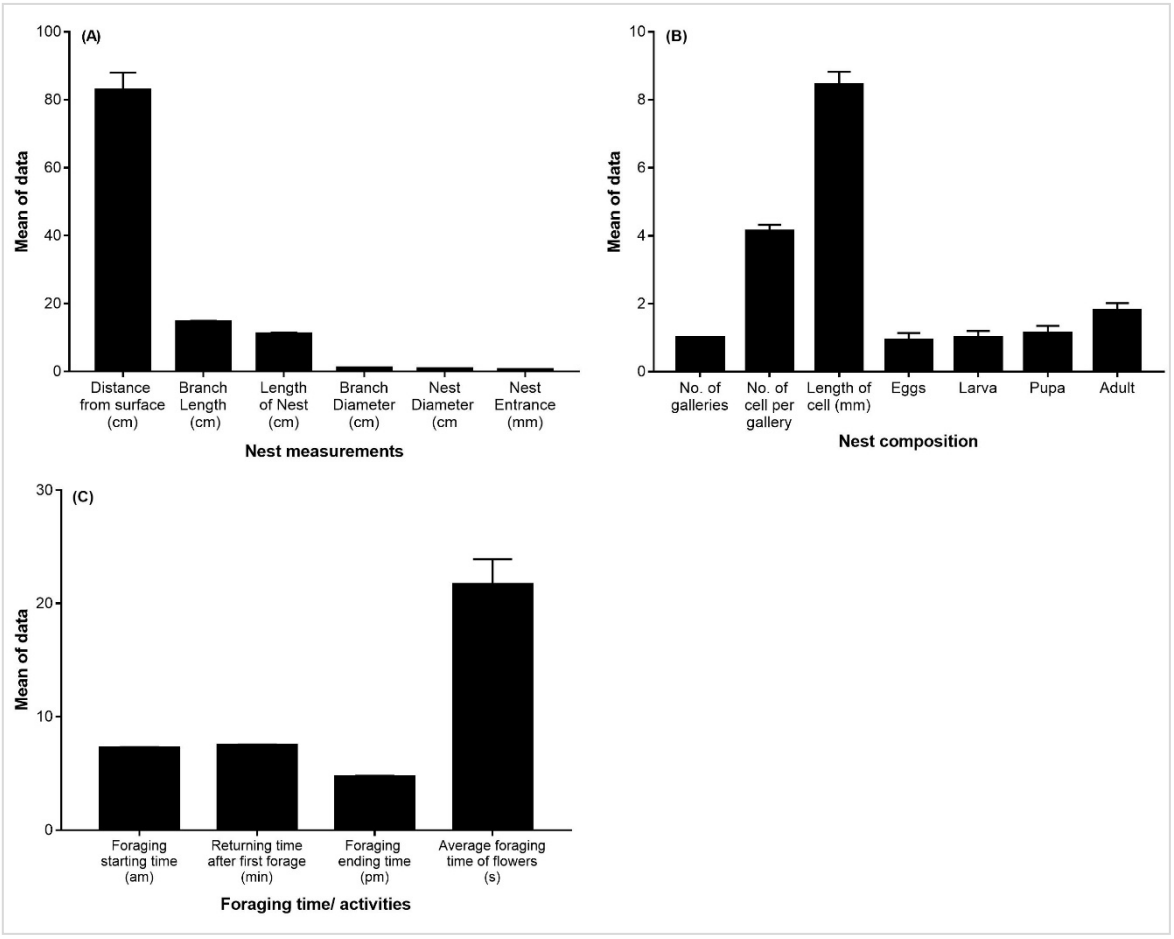

Fig 3. Data (mean ± SE) of recorded parameters of *Ceratina smaragdula* (A) nest measurements (B) nest composition, and (C) foraging time and activities.

Discussion

The small carpenter bee (*C. smaragdula*) preferred nesting on field sides, followed by roadsides and houses. The possible reason for this choice (nesting preference) could be the low disturbances in the field sides. Vickruck and Richards (2012) found that *Ceratina* spp. prefer open nesting sites exposed to more sunlight compared to shady sites. Thus, fields and roadsides are open and sunny. That favors the nesting preference of *C. smaragdula.* Ravenna grass was the most preferred nesting material because this grass is easily chewable and soft from the middle part. Our findings are in accordance with a previous study where *C. smaragdula* bees prefer to nest in Ravenna grass and near the field sides (Ali et al., 2016). A previous study reported the nesting in Siam weed and Mulberry (Malaipan & Orostrirat, 1992); instead, we found some nests in common Reed, *Phragmites australis* and Wheat, *Triticum aestivum,* stored straws. However, some common Asiatic *Ceratina* also prefer to nest in weeds (Yogi & Khan, 2014). Thus, the diversity of nesting material is evident from the literature. This diversity might be due to the diversified experimental area and the availability and abundance of their preferred nesting material in that area.

C. smaragdula bees hibernate from October to February, start mating in March, hatch their first generation in late April to early May, and peak population abundance from June to August. The green metallic small carpenter bees remain active during summer, prepare for hibernation at the start of winter, and peak pollination activity during warm and humid weather conditions (Shiokawa, 1969). Likewise, the data of the present study showed that the period from April to September is warm and humid in Pakistan, and *C. smaragdula* bees actively pollinated the crops, wild plants, and weeds. Gerling et al. (1982) also reported that carpenter bees were active in hot weather and remained in hibernation during the cold/winter.

The data revealed that *C. smaragdula* bees prefer to build their nest above the soil's surface in various nesting materials. The nest branch length, inside nest length, branch diameter, nest diameter, and nest entrance relatively vary from nest to nest as well as locations. These findings are consistent with those of Ali et al. (2016), who reported a few comparable characteristics regarding the nesting of *C. smaragdula*. The insects mainly consider avoiding the risk of predators, pests, diseases, and adverse conditions for nesting preferences (Meunier, 2015; Huang et al., 2020).

We found that *C. smaragdula* bees completed their life cycle from 4-5 weeks and produced 3-4 generations per year. These findings are comparable with previous studies, which reported that *C. smaragdula* bees completed their life cycle in 28-32 days (Malaipan & Orostrirat, 1992; Ali et al., 2016). The weather also has a significant impact on the life cycle, population dynamics, and seasonal activities (Batra, 1967; Shiokawa, 1969; Batra, 1976).

The small carpenter bees preferred linear nesting with one gallery per nest. Linear nesting is suitable for studying social interaction and intra-nest behavior (Rehan et al., 2009). Our data showed that the cells in the gallery ranged from 3-5 cells/nest (mean: 4.13), and the cell lengths were from 6.0 to 11.0 mm (mean: 8.44 mm). These results are partially consistent with a previous study that reported a cell length of 8.48 mm, but the mean brood cells/nest was less (2.70) (Ali et al., 2016) than our recorded mean (4.13 cells/nest).

Our data revealed that foraging started early in the morning (7.27 am) and ceased in the afternoon (4.71 pm), with an average foraging duration of 21.67 seconds at different flowers. The bees visited mainly cucurbits, fruit trees, wildflowers, and weeds. These results are consistent with those of Ali et al. (2016). We found that *C. smaragdula* visited different crops potentially for pollination, and it is confirmed by previous studies (Daly et al., 1971; Batra, 1976; Burgett et al., 2005). These carpenter bees may be referred to as polylectic with broad ecological, distributional, and pollination ranges.

Moreover, the growing urbanization and the transformation of agricultural lands into commercial and residential colonies were also thought to substantially impact the population of small carpenter bees. Conclusively, the population of *C. smaragdula* needs to be closely monitored, and precautions must be taken to prevent its decline due to its significant role in pollination. Ravenna grass is native to the area; artificial nests should be provided to the bees to compensate for their habitat loss. The artificial nests may be used as pollinators for other commercially economical crops or in greenhouses.

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Authors' Contribution

H.A.: Conceptualization, Methodology, Validation, Formal analysis, Writing-Original Draft, Supervision.
J.I.: Conceptualization, Methodology, Validation, Formal analysis, Writing-Review & Editing, Visualization, Funding acquisition.
M.A.: Methodology, Investigation, Data Collection, Data Curation, Writing-Original Draft.
F.S.: Conceptualization, Investigation, Validation, Data Curation, Project administration.
H.M.K.A.: Formal analysis, Writing-Review & Editing, Visualization.
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M.H.: Formal analysis, Validation, Writing-Review & Editing.
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Declaration of Competing Interest

The authors declare no conflict of interest.

Data availability statement

All data is provided within the article.

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Supplementary Material

Table S1. Architecture of *Ceratina smaragdula* nests collected from different localities of Swabi district in Khyber Pakhtunkhwa Province, Pakistan.

Nest measurements of *C. smaragdula*						
Nest number	**Distance from surface (cm)**	**Branch length (cm)**	**Length of nest (cm)**	**Branch diameter (cm)**	**Nest diameter (cm)**	**Nest entrance (mm)**
1	112.24	13.79	10.3	1.3	1.0	0.5
2	86.36	16.77	13.12	0.9	0.7	0.6
3	114.30	12.95	10.15	1.1	0.8	0.5
4	68.58	13.87	10.35	1.0	0.6	0.4
5	106.68	12.98	9.62	1.2	0.9	0.5
6	81.28	14.59	11.11	1.0	0.8	0.6
7	76.20	12.66	9.17	1.0	0.8	0.5
8	85.88	13.86	11.19	1.1	0.9	0.5
9	73.34	16.83	12.31	1.0	0.7	0.6
10	61.18	15.92	12.19	1.2	0.8	0.5
11	48.26	14.98	11.13	1.4	0.9	0.6
12	62.26	15.55	12.21	1.1	0.9	0.7
13	80.80	13.32	10.42	1.2	0.8	0.5
14	73.66	15.75	11.87	1.1	0.7	0.5
15	110.12	14.85	12.16	1.0	0.6	0.4
Mean ± SD	82.74 ± 20.19	14.58 ± 1.37	11.15 ± 1.14	1.11 ± 0.13	0.79 ± 0.12	0.53 ± 0.08

Table S2. Composition of *Ceratina smaragdula* nests collected from different localities of Swabi district in Khyber Pakhtunkhwa Province, Pakistan.

Nest composition of *C. smaragdula*							
Nest number	**No of galleries**	**No of cells per gallery**	**Length of cell (mm)**	**Contents of galleries**			
				Eggs	**Larva**	**Pupa**	**Adult**
1	1	4	8.0	1	0	1	2
2	1	5	11.0	2	1	0	3
3	1	4	10.0	2	2	0	1
4	1	4	8.0	1	1	1	2
5	1	5	7.4	0	1	2	2
6	1	3	7.0	0	0	1	2
7	1	4	8.0	0	1	1	1
8	1	5	6.0	2	2	0	2
9	1	3	9.0	1	0	1	1
10	1	4	10.0	1	2	1	1
11	1	4	8.0	0	1	1	3
12	1	5	6.9	1	1	2	3
13	1	5	8.0	1	0	2	2
14	1	4	8.3	2	2	3	0
15	1	3	11.0	0	1	1	2
Mean ± SD	1.00 ± 0.00	4.13 ± 0.74	8.44 ± 1.48	0.93 ± 0.80	1.0 ± 0.76	1.13 ± 0.83	1.80 ± 0.86

Table S3. Foraging time/activities of *Ceratina smaragdula* nests collected from different localities of Swabi district in Khyber Pakhtunkhwa Province, Pakistan.

Nest number	Foraging starting time (am)	Returning time after first forage (min)	Foraging ending time (pm)	Average foraging time of flowers (s)
1	7.25	7.26	4.55	28.00
2	7.17	7.40	5.05	18.00
3	7.10	7.11	4.30	23.00
4	7.15	7.20	5.02	13.00
5	7.00	7.30	5.15	09.00
6	7.28	7.40	4.47	17.00
7	7.30	7.45	4.52	21.00
8	7.22	7.30	4.37	12.00
9	7.35	8.00	4.39	35.00
10	7.31	7.33	4.56	14.00
11	7.20	7.27	5.00	35.00
12	7.42	8.00	4.32	33.00
13	7.12	7.56	4.56	16.00
14	7.23	7.49	5.15	30.00
15	8.00	8.18	5.30	21.00
Mean ± SD	7.27 ± 0.23	7.48 ± 0.41	4.71 ± 0.35	21.67 ± 8.67