



Sensilla of the Western Flower Thrips, *Frankliniella occidentalis* (Pergande) (Thysanoptera, Thripidae)

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ABSTRACT

The sensilla of insects play important roles in odor, taste, the feeling environment, and some sensory functions, which are closely associated with insect host locating, feeding, habitat searching, courtship, mating, and oviposition. In this study, we used a scanning electron microscope to observe the external morphology of nymph and adult *Frankliniella occidentalis* sensilla on antennae, compound eyes, legs, mouthparts, wings and tail. The results show that three main types of sensilla are located on the antennae: sensilla trichodea, sensilla chaetica, and sensilla basiconica. Among them, sensilla trichodea are the most abundant, followed by sensilla chaetica. Sensilla basiconica on antennae are divided into seven sub-styles, including longer sensilla (L-sensilla basiconica, long sensilla basiconica), shorter sensilla (angle sensilla basiconica, bud sensilla basiconica), and thicker and bigger sensilla (stick sensilla basiconica, fork sensilla basiconica, and finger sensilla basiconica). Only two fork sensilla basiconica were found, located on the dorsal part of the first flagellum subsegment and the ventral part of the second flagellum subsegment, respectively. Seven sensillum types were found on the legs: sensilla trichodea, sensilla chaetica, sensilla basiconica, sensilla ear washing buob-shaped, mamillary sensilla, sensilla campaniform, and Böhm bristle. About 60% of them are sensilla chaetica. Only one sensillum type was found on compound eyes: sensilla chaetica. In addition, some sensillum types were also found on the mouthparts, wings and tail, respectively. In the study, we observed the type, morphology, and distribution of sensilla on antennae, legs, compound eyes, and other regions of nymph and adult *F. occidentalis*, forming a base for future electrophysiological and behavior experiments on *F. occidentalis*.

Introduction

The western flower thrips, *Frankliniella occidentalis* (Pergande) (Thysanoptera, Thripidae), also called alfalfa thrips, were originally discovered in Hawaii in 1955. In China, they were first reported in Beijing in 2003 (Du et al., 2005). *F. occidentalis* has become a dominant thrips species, spread across Europe, Asia, Americas, Africa, and Oceania, and has been a worldwide invasive species since the 1980s (Felland et al., 1995; Kirk and Terry, 2003; Zhang et al., 2012). *F. occidentalis* are plant-feeding insects with piercing-sucking mouthparts and have a broad host plant range, pierce plant cells, and actively suck up their contents, causing serious damage to agricultural and ornamental crops. As vectors, these pests can transmit viruses by injecting saliva for feeding, such as groundnut ringspot virus, tomato spotted wilt virus, impatiens necrotic spot virus, etc (Jones et al., 2005). *F. occidentalis* are worldwide insect pests of vegetables and some crops. Their wide host

range, better adaptation, and high resistance make them extremely difficult to effectively control.

The sensilla of insects are the basic unit of the chemoreceptors, mechanoreceptors, and hygroreceptors, constituted by the association of sensory cuticular structures and sensory cells, and are specialized in receiving and transmitting signals or stimuli from and to the insect's central nervous system.

The sensilla of insects play important roles in habitat searching, host plant selection, courtship, mating, oviposition, sensing various chemical and physical stimuli of the environment, and regulating an insect's behavior (Schneider and Seibt, 1969; Clyne et al., 1997; Bruce and Cork, 2001; Park and Hardie, 2002; Zacharuk, 1980; Zhang et al., 2007). The antennae of insects are the primary structures where various sensilla are distributed to obtain environmental information and communicate chemically. Examples are sensilla trichodea, sensilla chaetica, sensilla basiconic, etc. The type and amount of sensilla are not the same between different insect species, and are even not the same between different

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sexual insects of one species. Different types of sensilla usually have different functions. Some sensilla can detect host volatile chemicals. Because there are many micropores on sensilla, odor molecules enter the lymphatic fluid of sensilla through these micropores. After being recognized by odorant binding protein, odor molecules are transported to odorant receptor and G-protein coupling signal pathway are started, causing changes in membrane potential and stimulating nerves. They are transmitted to central nervous system via axon, and then send out finger signals after brain integration So as to produce related olfactory behavioral response. Therefore, we can use plant volatile chemicals to lure pests, or through olfactory relative gene silencing, so as to regulate the behavior of pests for reducing the harm to crops.

Studying the olfactory mechanism of insects is critical for disrupting olfactory-mediated behaviors. The location, number, and fine structure of sensory organs in the pecibarium and cibarium of *F. occidentalis* have been reported (Hunter and Ullman, 1994), whereas the sensilla on antennae, legs, compound eyes, mouthparts, wings and tail of *F. occidentalis* have a few yet been investigated. Therefore, the aim of this study was to describe the type, morphology, and location of sensilla on antennae, legs, compound eyes and other regions of *F. occidentalis*. The results are beneficial for further research on the function of various sensilla, understanding the chemical communication mechanism and olfactory system, and providing a better basis for developing a highly effective strategy that would disrupt olfactory-mediated behaviors.

Material and Methods

Insects

F. occidentalis were collected from vegetable greenhouses at the Langfang Experimental Station of the Chinese Academy of Agricultural Sciences in Hebei Province, China. Subsequently, *F. occidentalis* were mass reared in the laboratory, and a laboratory colony was established and maintained at 26 ± 1 °C, a $60 \pm 5\%$ relative humidity (RH), and a photoperiod of 14:10 light:dark (L:D).

Scanning electron microscope (SEM)

We individually immersed 10 second instar nymphs, 10 female adults, and 10 male adults in 70% ethanol. The scales were removed with VGT-2127QTD ultrasonic cleaning (Shenzhen Verygood Science and Technology Co., Ltd., Shenzhen, China) for 3 s. Specimens were dehydrated in 70% ethanol for 24 h, dehydrated through a graded ethanol series (80%, 90%, 95%, and 100%) for 20 min each, and were then dehydrated again in 100% ethanol solution for 20 min. Afterward, specimens were critical-point dried for 1 h with CPD 030 (Micro Technology Hong Kong Ltd., Hong Kong, China), and then mounted on a holder from two sides, the dorsal side and ventral side, using double-sided adhesive tape and gold coated with the Eiko IB-3 Ion sputter coater (Hitachi, Tokyo, Japan). Sensilla were observed and micrographs were captured from different directions at 10 kV using the QUANTA 200 FEG scanning electron microscope (Feicompany, Hillsboro, OR., USA) (Lan et al., 2020).

Statistical analysis and classification

Sensilla on antennae, legs, compound eyes, mouthparts, wings and tail were identified and measured. Classification of the sensillum was based on the Schneider's terminology (Schneider, 1964). The lengths

and diameters per sensillum were measured using the Image-Pro plus software (Media Cybernetics, Bethesda, MD., USA).

Results

The adult antenna of *F. occidentalis* consist of three segments: the scape, the pedicel, and the flagellum. The flagellum is composed of six subsegments (Figure 1A). The former part of the first, the third, the fourth, and the fifth subsegment is brown, and is darker than in the latter part, and the others are maple-colored. The connection between the second and third antennal segment is uniform with no thicker ring. Fork sensilla basiconica are located in the third and fourth segments. Four types of sensilla were observed on the antenna of *F. occidentalis*: trichodea, chaetica, basiconica, and mamillary sensilla. The legs of *F. occidentalis* consist of the coxa, trochanter, femur, tibia, tarsus, and former tarsus. Seven types of sensilla were observed on the legs: sensilla trichodea, sensilla chaetica, sensilla basiconica, sensilla ear washing buob-shaped, mamillary sensilla, sensilla campaniform, and Böhm bristle. Only one sensilla type was found on the compound eyes of *F. occidentalis*: sensilla chaetica. Four types and six subtypes of sensilla were observed on the mouthparts of *F. occidentalis*, namely short sensilla trichodea, long sensilla basiconica, finger sensilla basiconica, L-sensilla basiconica, sensilla ear washing buob-shaped, and mamillary sensilla. Sensilla trichodea, long sensilla basiconica and long sensilla chaetica were observed on the wings of *F. occidentalis*. On the tail of *F. occidentalis*, there are four subtypes of sensilla: short sensilla trichodea, L-sensilla basiconica, long sensilla chaetica and short sensilla chaetica (Table 1, 2, 3).

Sensilla chaetica in antenna

Sensilla chaetica are generally straight or slightly curved, rugged and powerful, sharp at the tip, and divided into three subtypes: long sensilla chaetica, short sensilla chaetica, and sword-like sensilla chaetica.

Long Sensilla chaetica are 15.11–22.66 μm in length and 0.9v in basal diameter, and are significantly finer than sword-like sensilla chaetica (Figure 1B), curved slightly, thick at the base, and gradually become finer from the base to the tip with a smooth surface. They are distributed on the sixth circle of the first flagellar subsegment of the second instar nymph and the scape, the pedicel, and the flagellar first–fourth subsegments of adults, and are mainly concentrated on the distal region of each segment. They are not abundant (about five sensilla on each segment), and have sockets (1.58–1.78 μm in height, 3.30–3.88 μm in basal diameter).

Short sensilla chaetica have a 10.05–13.68 μm length and a 1.58–1.79 μm basal diameter, and are shorter and thicker than long sensilla chaetica (Figure 1C), curved slightly, obviously sharp at the tip, and distributed on the distal part of the second flagellar subsegment of second instar nymphs. They are not abundant, have longitudinal striations consisting of a punctum on the surface, have sockets (about 1.48 μm in height, 3.72 μm basal diameter), and have no mortar shape gap between the sensillum and socket.

These sensilla have a sword-like shape (Figures 1D, E), are rugged and powerful, sharp at the tip, have obvious longitudinal striations at the surface, and are present in the distal part of the second flagellar subsegment of the second instar nymph and the scape, the pedicel, and the flagellar first–fourth subsegments of adults. They are not abundant, and have a length of 18.26–23.67 μm and 1.8–2.5 μm basal diameters.

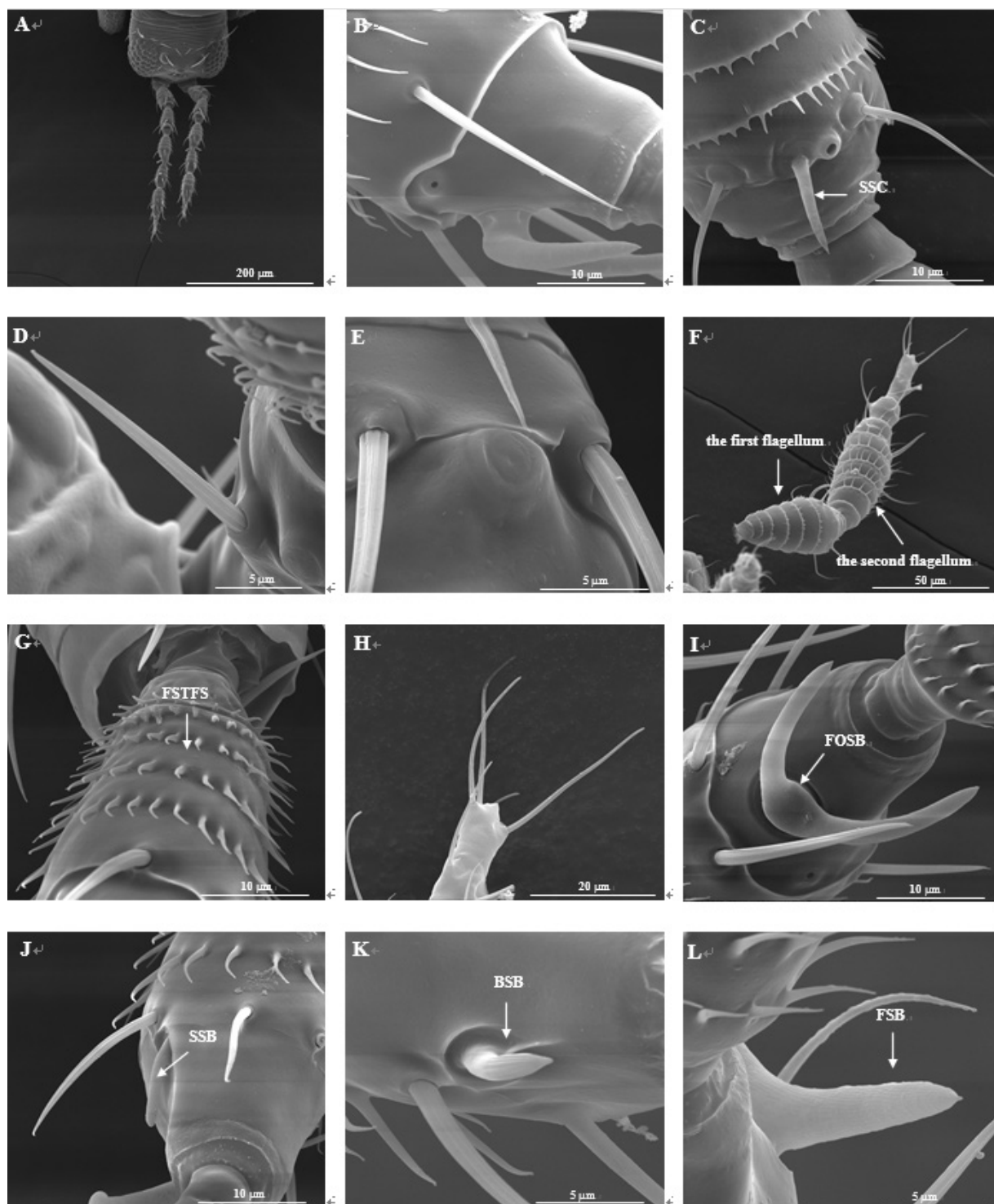


Figure 1 Types of sensilla in *Frankliniella occidentalis* antennae: (A) female antenna, (B) long sensilla chaetica, (C) short sensilla chaetica (SSC), (D,E) sword-like sensilla chaetica, (F) sensilla trichodea on the first and second flagellum of nymphs, (G) female sensilla trichodea (FST), (H) long sensilla basiconica, (I) fork sensilla basiconica (FOSB), (J) stick sensilla basiconica (SSB), (K) bud sensilla basiconica (BSB), (L) finger sensilla basiconica (FSB).

Sensilla trichodea in antenna

Sensilla trichodea are the most frequent type and mainly distributed in the first and second subsegments of the second instar nymph flagellum, as well as from the first to the fourth subsegment of the adult flagellum.

Sensilla trichodea are arranged in five circles on the first subsegment of second instar nymphs (Figure 1F). They are small, have a wide basal part,

are inclined and straight or slightly curved toward the apex of the segment, and become finer from the base to the tip. Sensilla trichodea, from the first to the third circles, are smaller (0.2–1.6 μm length, 0.2–1.4 μm basal width), and the fifth and sixth circles are relatively longer (0.48–2.8 μm length, 0.46–2.1 μm basal width). The distal portion of the first subsegment of the second instar nymph has four longer sensilla trichodea (16.5–19.3 μm length, 1.2–1.5 μm basal diameter) with mound-like basal sockets.

Table 1
Types and distribution of sensilla in *F. occidentalis*.

Type	Subtype	Antennae	Legs	Compound eyes	Mouthparts	Wings	Tail
Sensilla Chaetica	Long sensilla chaetica	Y	Y	—	—	Y	Y
	Short sensilla chaetica	Y	—	—	—	—	Y
	Sword-like sensilla chaetica	Y	Y	—	—	—	—
Sensilla Trichodea	Short Sensilla Trichodea	Y	Y	—	Y	Y	Y
	Long Sensilla Trichodea	—	Y	Y	—	—	—
Sensilla Basiconica	L-sensilla basiconica	Y	—	—	Y	—	Y
	Fork sensilla basiconica	Y	—	—	—	—	—
	Stick sensilla basiconica	Y	—	—	—	—	—
	Bud sensilla basiconica	Y	—	—	—	—	—
	Finger sensilla basiconica	Y	—	—	Y	—	—
	Angle sensilla basiconica	Y	Y	—	—	—	—
	Long sensilla basiconica	Y	Y	—	Y	Y	—
	Shot Sensilla Basiconica I	—	Y	—	—	—	—
	Shot Sensilla Basiconica II	—	Y	—	—	—	—
	Sensilla Campaniform	—	—	Y	—	—	—
Sensilla Mamillary	—	—	Y	—	Y	—	
Sensilla Ear Washing Buob-Shaped	—	—	Y	—	Y	—	
Böhm Bristle	—	—	Y	—	—	—	

Note: "Y" indicates it is there, "—" indicates it is not found there.

Table 2
Morphological types of antennal sensilla in *F. occidentalis*.

Type	Subtype	Length (µm)	Basal diameter (µm)	Tip	Wall	Shape	Socket
Sensilla Chaetica	Long sensilla chaetica	15.11–22.66	0.95–1.31	—	Smooth	slightly curved	height 1.58–1.78 µm, basal diameter 3.30–3.88 µm
	Short sensilla chaetica	10.05–13.68	1.58–1.79	—	—	slightly curved	height 1.48 µm, basal diameter 3.72 µm
	Sword-like sensilla chaetica	18.26–23.67	1.8–2.5	Sharp	—	—	—
Sensilla Trichodea	—	0.2–19.3	0.2–1.5	—	—	Straight or slightly curved	mound-like basal sockets
Sensilla Basiconica	L-sensilla basiconica	22.25–26.56	0.88	—	—	—	—
	Fork sensilla basiconica	12–16	2.5–3.5	Sharp	—	—	—
	Stick sensilla basiconica	7.6–9.86	1.8–2.3	—	—	—	—
	Bud sensilla basiconica	4.0–4.5	1.5–1.8	Blunt	—	—	—
	Finger sensilla basiconica	10.09–16.29	1.59–3.19	—	—	—	—
	Angle sensilla basiconica	2.13–2.68	0.58–0.91	—	Smooth	—	—
	Long sensilla basiconica	13.8–17.7	0.9–1.1	—	Smooth	curved	height 0.8–1.2 µm, diameter 1.8–2.2 µm

Table 3
Morphological types of sensilla in *F. occidentalis* legs.

Type of sensilla	Subtype	Length (µm)	Basal diameter (µm)	Tip	Wall	Shape
Sensilla Basiconica	Angle Sensilla Basiconica	3.85–4.01	0.76–0.91	—	Smooth	—
	Shot Sensilla Basiconica I	5.86–6.96	0.56–0.82	—	Smooth	slightly curved
	Shot Sensilla Basiconica II	7.62–9.07	1.18–1.86	—	longitudinal striations	—
Sensilla Chaetica	Long Sensilla Basiconica	22.63–27.12	1.91–2.37	—	—	—
	Sword-Like Sensilla Chaetica	8.65–10.91	0.78–0.97	—	longitudinal striations	—
Sensilla Trichodea	Long Sensilla Chaetica	18.26–20.66	1.88–2.12	Sharp	longitudinal striations	—
	Short Sensilla Trichodea	0.85–1.06	0.36–0.43	—	Smooth	—
Sensilla Campaniform	Long Sensilla Trichodea	4.31–5.62	0.53–1.14	—	Smooth	—
	—	1.02–1.33	1.0–1.57	Sharp	Smooth	—
Sensilla Mamillary	—	0.52–0.71	1.06–1.58	—	—	—
Sensilla Ear Washing Buob-Shaped	—	1.02–2.33	0.51–1.23	—	—	—
Böhm Bristle	—	1.21–5.38	0.23–0.51	—	—	—

Sensilla trichodea on the second subsegment of the second instar nymph are similar to the shape of those on the first subsegment (Figure 1F), but are arranged in six circles. From the first to the fifth circles, they are abundant, arranged regularly, have a 30–75° angle with the surface of the antenna, and are relatively longer and thicker (4.4–6.2 µm length, 0.62–0.88 µm basal diameter). Their lengths in the sixth circle are significantly different (0.5–8.3 µm length, 0.46–2.1 µm basal width). The distal portion on the second subsegment of second instar nymphs has two longer sensilla trichodea (17.8–19.6 µm length, 1.2–1.5 µm basal diameter) with mound-like basal sockets.

The morphological features of sensilla trichodea on the adult flagellum are similar to those on the nymph (Figure 1G). They are abundant, arranged regularly, and have a 6.5–10.7 µm length and a 0.6–0.8 µm basal diameter. However, some differences exist between sexes, or different antenna of one adult male. The females have five circles of sensilla trichodea arranged in the first subsegment of the flagellum, four circles in the second subsegment of the flagellum, and three circles in both the third and fourth subsegment of the flagellum. However, the males have six circles of sensilla trichodea in the first subsegment of the flagellum in the left antenna and four circles in the fourth subsegment of the flagellum in the right antenna, and the others are the same as in the female.

Sensilla basiconica in antenna

The base of sensilla basiconica is inserted into ring- or mound-like sockets. Sensilla basiconica can be divided into seven subtypes according to their morphologies: L-sensilla basiconica, finger sensilla basiconica, angle sensilla basiconica, bud sensilla basiconica, long sensilla basiconica, stick sensilla basiconica, and fork sensilla basiconica.

Long Sensilla Basiconica: These sensilla are long (22.25–26.56 µm length, 0.88 µm basal diameter), with subtle longitudinal striations on the surface, inserted into mound-like sockets, mainly distributed on the former region of each flagellum subsegment, and are not abundant (Figure 1H).

Fork Sensilla Basiconica: There are two fork-like shaped sensilla in each antenna (Figure 1I). One is distributed in the dorsal region of the first subsegment and the other is distributed in the ventral apical region of the second subsegment of the adult antennal flagellum. They are bigger, thicker, sharp at the tip, and have two arms for each sensillum that exhibit uneven symmetry and differences in length (12–16 µm) and diameter (2.5–3.5 µm).

Stick Sensilla Basiconica: These sensilla are stick-like shaped (Figure 1J), wholly thick from the base to the tip with longitudinal striations consisting of punctum on the surface, are not abundant, are sunken into a subsidence area (3.2–3.8 µm diameter), and are mainly distributed in the external and dorsal regions of the second subsegment and the dorsal region of the fourth subsegment of the adult antennal flagellum. The upper part of sensilla is a little finer than the base, and the apex is the most rounded and blunt of all types of sensilla of *F. occidentalis* mentioned in this study. Their length is 7.6–9.86 µm and basal diameters is 1.8–2.3 µm.

Bud Sensilla Basiconica: These sensilla are new bud-like shaped (Figure 1K), the least abundant, inserted into big sunken sockets (2 µm diameter), and mainly distributed in the former region of the second subsegment of the nymph flagellum and the third and fourth subsegments of the dorsal part of the adult flagellum. They are short (4.0–4.5 µm length) and thick (1.5–1.8 µm basal diameters), and are fine in the first one-third portion of the sensillum, thick again in the upper-middle portion, and fine at the tip. The tip is blunt.

Finger Sensilla Basiconica: These sensilla have a finger- or S-like shape, are generally inserted into relatively flat sockets, and are mainly distributed in the former part of the first and second subsegments of the nymph flagellum and the former part of the fourth subsegment of the adult flagellum (Figure 1L, Figure 2A). They are few in number and thick from the base to the tip (10.09–16.29 µm length, 1.59–3.19 µm basal diameter), with longitudinal striations consisting of punctum, inclined toward the apical antenna.

Angle Sensilla Basiconica: These sensilla are small, few in number, angle-like shaped with conic extremity and a smooth surface, mainly distributed in the basal scape of antenna (Figure 2B), and inserted into slight ring- and mound-like sockets. The length of angle sensilla basiconica is 2.13–2.68 µm, the basal diameter is 0.58–0.91 µm, and the tip diameters are approximately one-fourth smaller than the basal diameters.

L-Sensilla Basiconica: These sensilla are L-like shaped, and mainly distributed in the pedicel and the flagellum of the antenna (Figure 2C). They are longer (13.8–17.7 µm length) and finer (0.9–1.1 µm basal diameter), with a smooth surface, and become finer from the base to the tip. Their bases are slightly inclined or straight, and inserted into round table-like sockets (0.8–1.2 µm height, 1.8–2.2 µm diameter), but at the upper-middle region of the sensillum, they are significantly curved toward the apex of the segment.

Sensilla mamillary in antenna

These sensilla are small (0.21–0.27 µm height, 0.12–0.18 µm basal diameter), mamillary-like shaped (Figure 2D), and mainly distributed on the distal part of the scape and the third flagellar subsegment of the second instar nymph.

Sensilla basiconica in Leg

Angle Sensilla Basiconica: Angle sensilla basiconica are similar to those on the antennae, not abundant, inserted in protuberant sockets, randomly distributed in the coxa of the second instar nymph, and have a smooth surface (Figure 3A). Their length is 3.85–4.01 µm with basal diameter of 0.76–0.91 µm.

Shot Sensilla Basiconica I: They are small (5.86–6.96 µm lengths, 0.56–0.82 µm basal diameters), inserted in the protuberant sockets, and mainly distributed on the femur. Their surfaces are smooth and the tips are inclined slightly (Figure 3B).

Shot Sensilla Basiconica II: They are significantly smaller (7.62–9.07 µm length) and thicker (1.18–1.86 µm basal diameter) than shot sensilla basiconica I, and mainly present on the femur and the distal portion of tibia, with longitudinal striations on the surface (Figure 3C).

Long Sensilla Basiconica: They are thin and long (22.63–27.12 µm length, 1.91–2.37 µm basal diameter), have protuberant sockets in the base, and are mainly present on the former tarsus of the second instar nymph (Figure 3D).

Sensilla chaetica in Leg

Sword-Like Sensilla Chaetica: These sensilla are sword-shaped (Figures 3E,F), similar to the sensilla chaetica on antennae, inclined a little, relatively abundant, have a small and slightly protuberant cotyloid nest on the base, are mainly present on the femur and the dorsal tibia of legs, and have obvious and wide longitudinal striations on the surface. Their lengths are about 8.65–10.91 µm and the basal diameters are about 0.78–0.97 µm.

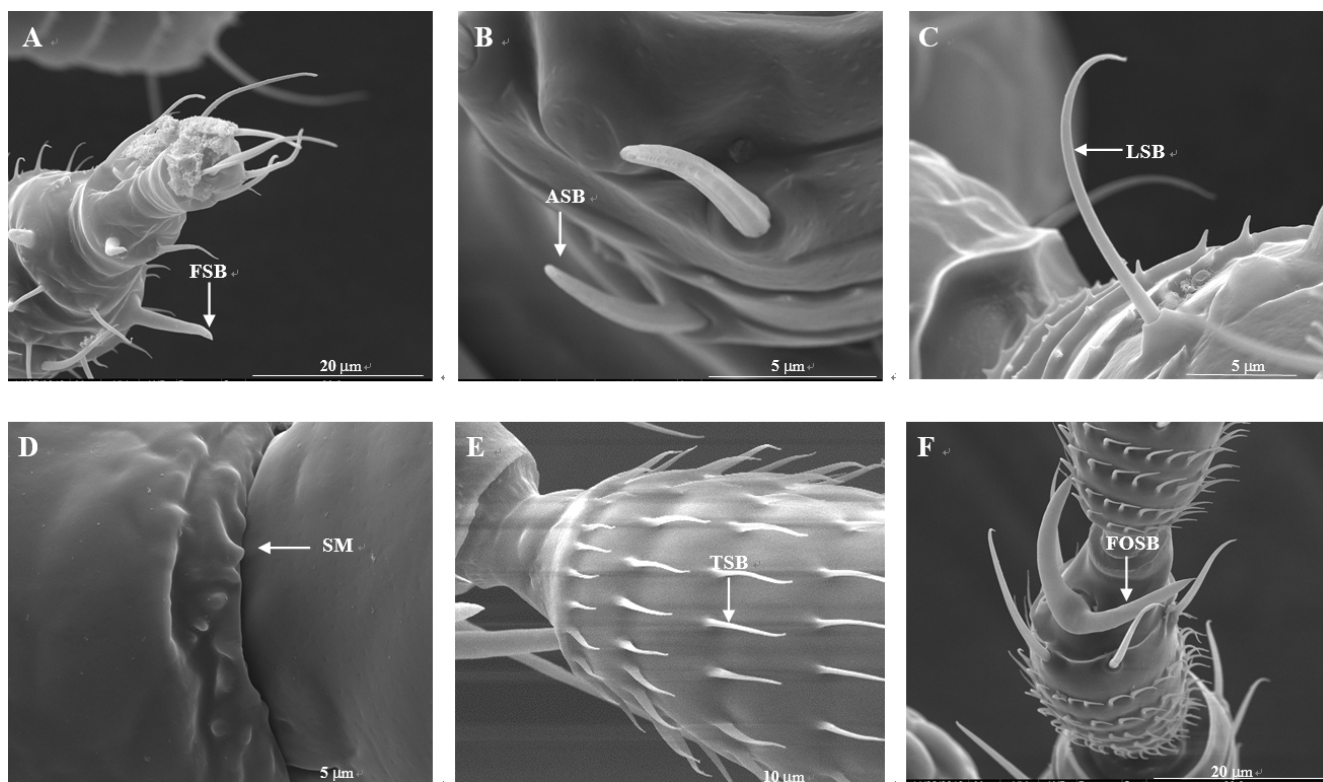


Figure 2 Types of sensilla in *Frankliniella occidentalis* antennae: (A) finger sensilla basiconica (FSB), (B) angle sensilla basiconica (ASB), (C) long sensilla basiconica (LSB), (D) sensilla mamillary (SM), (E) trichodea sensilla (TSB) and (F) fork sensilla basiconica (FOSB).

Long Sensilla Chaetica: These sensilla are thin and long, not abundant, have a tip inclined toward the apical segment, and are mainly distributed on the femur, where only this type of sensillum was observed (Figure 3G). They are sharp at the tip and have protuberant sockets at the base, with longitudinal striations on the surface. Their length is 18.26–20.66 µm with a basal diameter of 1.88–2.12 µm.

Sensilla trichodea in Leg

Short Sensilla Trichodea: These sensilla are short (0.85–1.06 µm length, 0.36–0.43 µm basal diameter), distributed on the coxa and the former tarsus of legs, and nearly stick in the surface of leg coxa (Figure 3H), with a smooth surface.

Long Sensilla Trichodea: A few of these sensilla are present on the former tarsus, and they nearly stick in the surface of the former tarsus (Figure 3I). They are 4.31–5.62 µm long and gradually become fine from the base to the tip, with smooth surfaces. The bases are flat, and about 0.53–1.14 µm wide.

Sensilla campaniform in Leg

These sensilla are peach-like or semicircle shaped (Figure 3J; 1.02–1.33 µm height, 1.0–1.57 µm basal diameter), expanded at the base and sharp at the tip, have a smooth surface, are situated at the distal portion of the trochanter, and inserted in sunken mortar nests whose diameters are 2.52–2.76 µm.

Sensilla mamillary in leg

These sensilla are mamillary-shaped (Figure 3K), abundant, smaller than sensilla ear washing buob-shaped (0.52–0.71 µm height,

1.06–1.58 µm basal diameter), and distributed at the ventral area and end of the femur.

Sensilla ear washing buob-shaped in leg

These sensilla are very small (1.02–2.33 µm length, 0.51–1.23 µm basal diameter), arranged in a row at the end of the coxa and the base of the femur, and have the typical shape of an ear washing buob (Figures 3L,M), with a round pot-like base and tapered tip.

Böhm bristle in Leg

Böhm bristles are present at the former tarsus edge (Figure 3N) and are more abundant. They have a length of 1.21–5.38 µm 0.23–0.51 µm basal diameter.

Sensilla in compound Eyes

Only one sensilla type was found on the compound eyes of *F. occidentalis*: sensilla chaetica (Figure 4), which are similar to sensilla chaetica on antennae and legs. They are thin and long (13.68–16.75 µm length, 0.98–1.32 µm basal diameter), inclined slightly, have a smooth surface, and are inserted uprightly in protuberant sockets that are among ommatidia.

Sensilla in other regions

Four types and six subtypes of sensilla were observed on the mouthparts of *F. occidentalis* (Figures 5), namely short sensilla trichodea, long sensilla basiconica, finger sensilla basiconica, L-sensilla

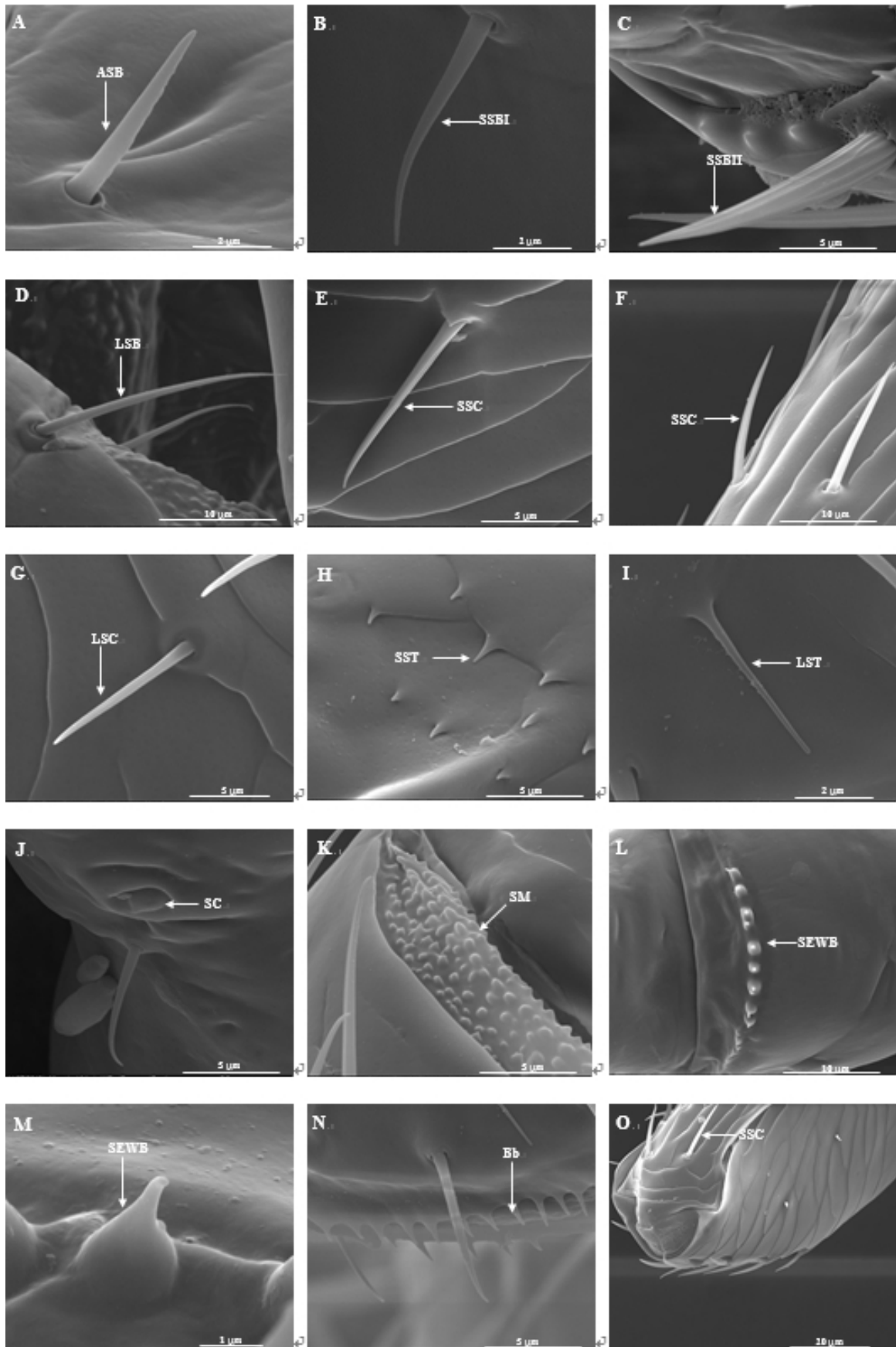


Figure 3 Types of sensilla in *Frankliniella occidentalis* legs. (A) angle sensilla basiconica (ASB), (B) shot sensilla basiconica I (SSBI), (C) short sensilla basiconica II (SSBII), (D) long sensilla basiconica (LSB), (E,F) sword-like sensilla chaetica (SSC), (G) long sensilla chaetica (LSC), (H) short sensilla trichodea (SST), (I) long sensilla trichodea (LST), (J) sensilla campaniform (SC), (K) sensilla mamillary (SM), (L,M) sensilla ears washing buob-shaped (SEWB), (N) Böhm bristle (Bb) and (O) sword-like sensilla chaetica (SSC).

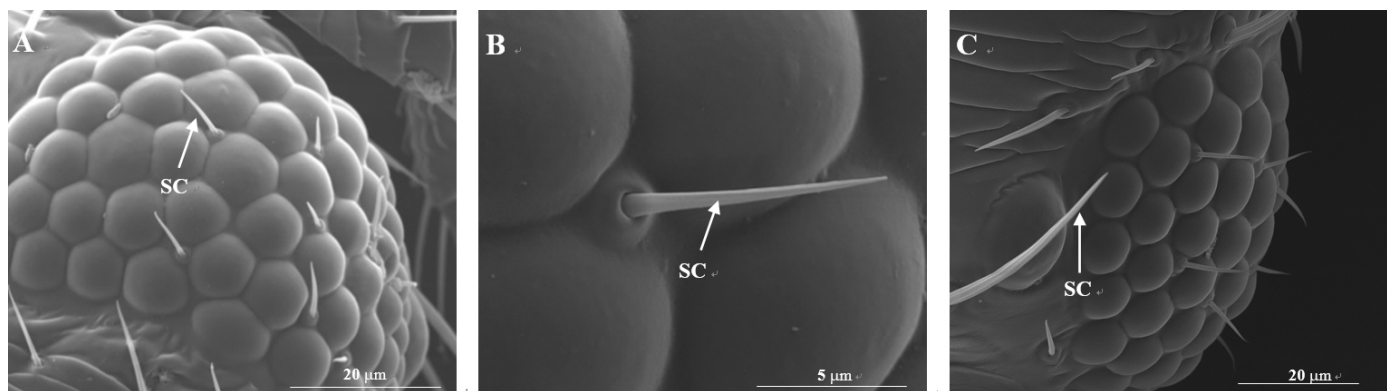


Figure 4 Types of sensilla chaetica in *Frankliniella occidentalis* compound eyes. (A,B,C) sensilla chaetica(SC).

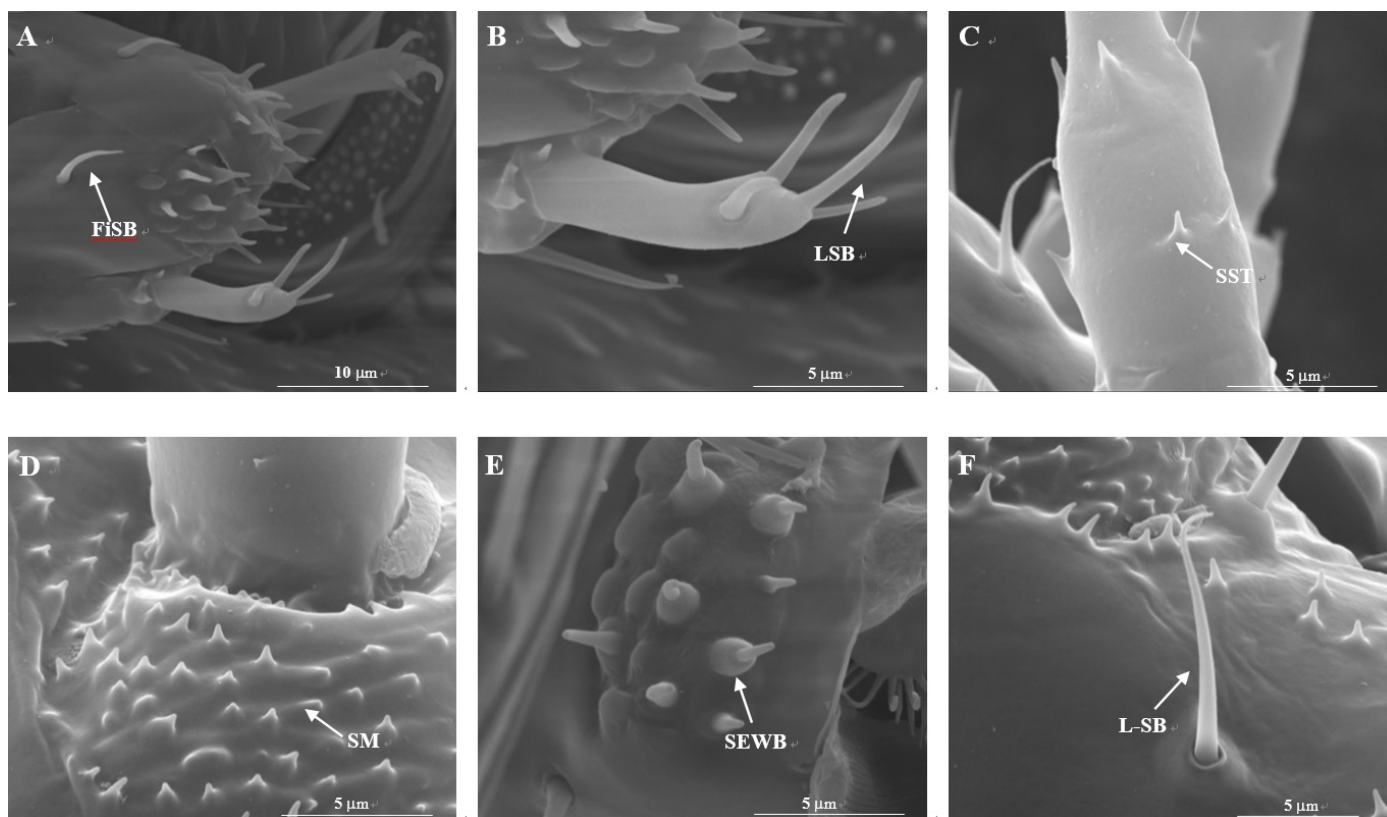


Figure 5 Types of sensilla in *Frankliniella occidentalis* mouthparts: (A) short sensilla trichodea (SST), (B) long sensilla basiconica (LSB), (C) finger sensilla basiconica (FiSB), (D) long sensilla basiconica (L-SB), (E) sensilla ear washing buob-shaped (SEWB), and (F) sensilla mamillary (SM).

basiconica, sensilla ear washing buob-shaped, and mamillary sensilla. Sensilla trichodea, long sensilla basiconica and long sensilla chaetica were observed on the wings of *F. occidentalis* (Figures 6). On the tail of *F. occidentalis*, there are four subtypes of sensilla (Figures 7): short sensilla trichodea, L- sensilla basiconica, long sensilla chaetica and short sensilla chaetica. And their morphologies are as stated above.

Discussion

Using electrophysiological experiments Schneider (Schneider, 1964) proved that the sensilla of insects have an olfactory function when recording the olfactory potential diagram of *Bombyx mori* antennae, which aroused scientists' interest in studying the function of antennal sensilla. Since, many sensilla of insects have been observed and

gradually identified, such as sensilla trichodea, sensilla chaetica, sensilla basiconica, sensilla campaniform, and sensilla coeloconica. Different types of sensilla usually play different roles. Generally, sensilla trichodea are sensitive to semiochemicals and probably responsible for finding mates (Almaas and Mustaparta, 1991; Wu, 1993; Du et al., 1995). For example, AlinOBP4 was strongly expressed in the multiporous sensilla trichodea and middle long sensilla basiconica of male *adelphocoris lineolatus* adults, suggesting a key role associated with sex pheromone and odorant detection (Wang et al., 2020). Sensilla chaetica are suggested to feel mechanical stimulus (Yang et al., 2001; Li et al., 2006). Compared with other sensilla, sensilla chaetica are straighter and longer, and more easily come into contact with mechanical stimulus (Schneider, 1964; Cuperus, 1983). Sensilla basiconica usually recognize host plant volatiles (Ochieng et al., 2000; Bleeker et al., 2004). Campaniform sensilla can

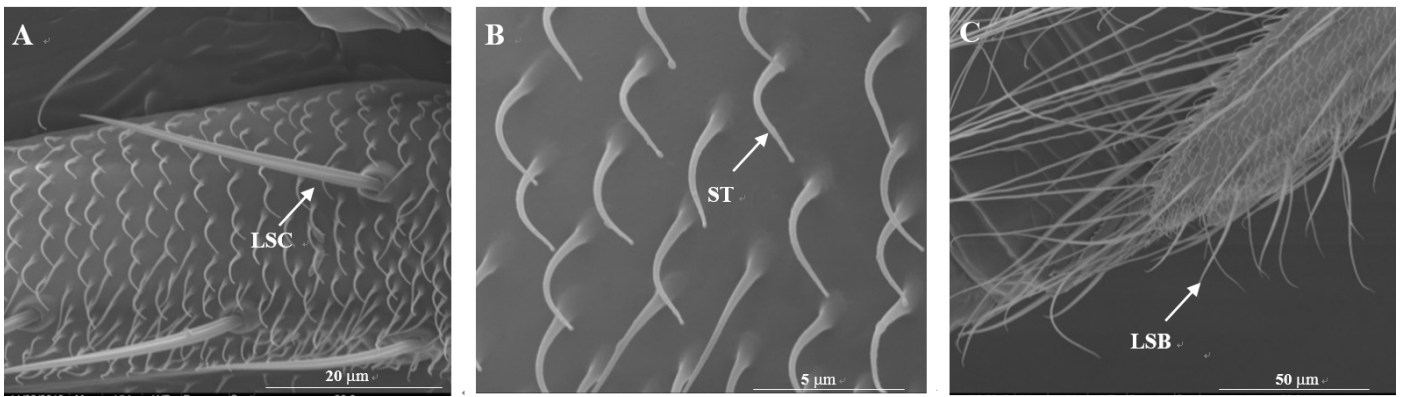


Figure 6 Types of sensilla in *Frankliniella occidentalis* wings: (A) long sensilla chaetica (LSC), (B) sensilla trichodea (ST), (C) long sensilla basiconica (LSB).

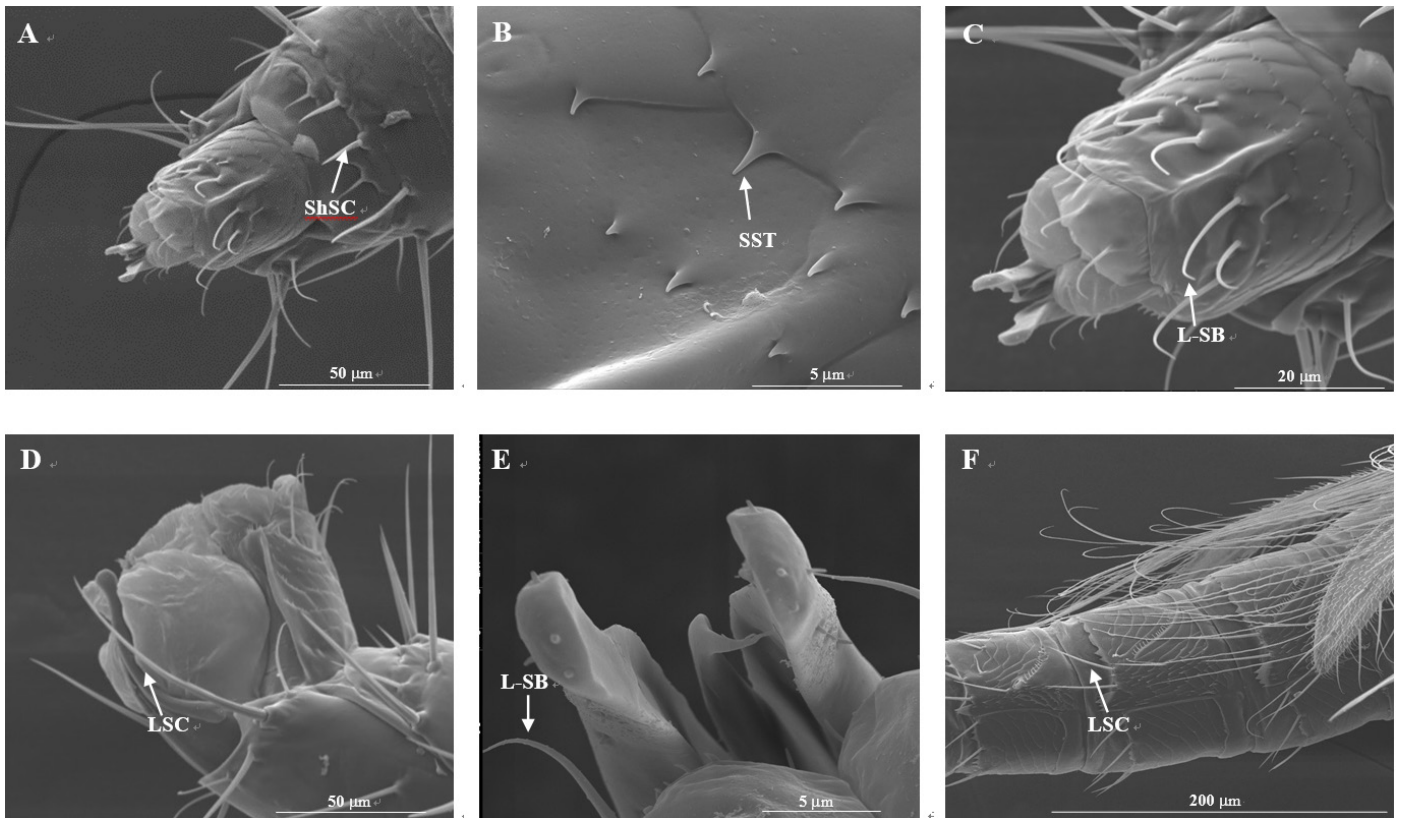


Figure 7 Types of sensilla in *Frankliniella occidentalis* tail: (A) short sensilla trichodea (SST), (B) long sensilla basiconica (L-SB), (C,E) long sensilla chaetica (LSC), (D,F) short sensilla chaetica (ShSC).

detect deformations of the exoskeleton arising from resisted movements or external perturbations (Dinges et al., 2021), and noise analysis of campaniform sensilla on both lepidopteran wings and dipteran halteres shows selectivity to two stimulus features related by a derivative, which are sufficient to explain spiking activity (Dickerson et al., 2021). In addition, different tastes, such as sweet, bitter, and leaf surface wax, were received through the tarsal sensilla of chrysomelidae by recording the electrophysiological responses of the sensilla (Yosano et al., 2020).

The internal morphology of the feeding structures (single mandible, paired maxillary stylets, paraglossal sensillum) of *F. occidentalis* was elucidated in order to clarify the feeding mechanisms of *F. occidentalis* and the possible function of stylet and paraglossal sensory structures in host location, feeding site selection and host choice (Hunter and Ullman, 1994). The distribution and ultrastructure of sensilla on the antenna of nymphae,

pupae and adults of *F. occidentalis* had also been observed under scanning electron microscope (Ding et al., 2010). But there are some differences in classification or nomenclature between this literature and our article. For example, sensilla basiconica in antennae were divided six sub-styles in this literature and seven sub-styles in our article. In addition, we find mamillary sensilla in antenna, which is not reported in this literature. The ultrastructure of antennal sensilla in adult *F. occidentalis* was reported in another literature (Li and Feng, 2013), which mainly observed antennal sensilla in adult *F. occidentalis*. While in this article, we observed the external morphology of nymph and adult *F. occidentalis* sensilla on antennae, compound eyes, legs, mouthparts, wings and tail. In addition, the description on morphology and distribution of some sensilla are more detailed. For example, we described the location and morphology in each subsegment of different instar nymphs and adults, etc.

In this study, we found four types of sensilla on *F. occidentalis* antennae. Among them, sensilla trichodea are the most abundant, followed by sensilla chaetica and sensilla basiconica, which presumably indicates that *F. occidentalis* antennal sensilla likely have important roles in recognizing general volatile substances in the environment and feeling mechanical stimulus. According to their morphology and distribution, antennal sensilla basiconica are divided into seven subtypes. Fork sensilla basiconica are particularly rare in other insect species. They are thicker, longer, and tapered at the tip, and may be responsible for recognizing host plant volatile compounds for feeding, host selection, searching for the oviposition location, mating, etc. Seven types of sensilla exist on the legs of *F. occidentalis*, most of which are sensilla chaetica, which indicates that the main function of sensilla on legs is likely to detect and respond to a mechanical stimulus. This conclusion is consistent with the function of sensilla chaetica on other insect legs reported in the literature (Eckweiler et al., 1989; Zhang et al., 2014). Sensilla chaetica on the compound eyes of *F. occidentalis* may have key roles in feeling a mechanical stimulus for protecting the eyes.

In this study, we preliminarily examined the type, morphology, and distribution of sensilla on the antennae, legs, compound eyes, and other regions of *F. occidentalis*, and then suggested the function of each type of sensillum. Future work will include an electroantennogram, single cell potential records, and the use of transmission electron microscopy for further understanding the specific function of each type of sensillum, which would provide a better basis for revealing the mechanisms of olfactory behaviors of *F. occidentalis*.

Conclusion

In this study, we determined the external morphology, type, and distribution of nymph and adult *Frankliniella occidentalis* sensilla on antennae, compound eyes, legs, and other regions, to provide the necessary background information for further understanding the recognition mechanism of host locating, courtship, oviposition, and so on. This forms a base for future electrophysiological and behavior experiments on *F. occidentalis* aimed at the development of a new control strategy.

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Conflicts of interest

The authors declare no conflict of interest.

Author contribution statement

ZKZ conceptualization, formal analysis, investigation, data curation, writing—original draft preparation. ZKZ and ZRL writing—review and editing.

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