ORIGINAL PAPER

Behavioral pattern of generalist and specialist insect pests to brassicaceous leaf cuticular *n*-alkanes and free fatty acids

Nayan Roy[1]

Abstract

The role of leaf cuticular wax of cabbage, *Brassica oleracea* L., rapeseed, *B. campestris* L., and Indian mustard, *B. juncea* L. in host preference by two generalists, *Spilarctia obliqua* Walker and *Pieris brassicae* L., and a specialist, *Plutella xylostella* L. was investigated under laboratory conditions. A total of 25 *n*-alkanes from n-C_{14} to n-C_{36} and 15 free fatty acids (FFAs) from $C_{12:0}$ to $C_{22:0}$ were detected from leaf cuticular wax of three crops with significant variations in their respective quantities (µg leaf^{-1}). The most preferred wax chemicals were consisted of 5 *n*-alkanes (n-C_{16}, n-C_{18}, n-C_{20}, n-C_{22}, n-C_{30}) and 5 FFAs ($C_{12:0}$, $C_{16:0}$, $C_{18:3}$, $C_{18:2}$, $C_{18:1}$) for the pests. Highest attraction index (AI%) and oviposition preference index (OPI%) were in the order of *P. brassicae* > *P. xylostella* > *S. obliqua* and *P. xylostella* > *P. brassicae* > *S. obliqua*, respectively, toward the combined synthetic mixture (5 *n*-alkanes + 5 FFAs) treated leaf of cabbage due to higher amount of wax chemicals in the specific combination. Both generalist and specialist have same patterns of olfaction and oviposition preferences with different magnitude of responses. Thus, the synthetic blends of same 5 *n*-alkanes and 5 FFAs of the most preferred cabbage cultivar might be used as lure to develop baited trap as well as less preferred crop (rapeseed and Indian mustard) species might be used as main crop with cabbage as trap crop against the pests for their sustainable ecological management in near future.

Keywords *Brassica oleracea* · *B. campestris* · *B. juncea* · *Spilarctia obliqua* · *Pieris brassicae* · *Plutella xylostella* · *n*-alkanes · Free fatty acids · Baited trap · Trap crop

Introduction

Brassicaceous vegetables like cabbage and oil seeds are most popular around the world in respect of its great potential for providing food security (Biswas et al. 2019; Gawariya et al. 2015; Neik et al. 2017; Obermeier et al. 2022; Tandayu et al. 2022). Cabbage, *Brassica oleracea* L. var. *capitata*, is one of the most important vegetables grown throughout the world (Koza et al. 2018). After China, India is the largest grower of cabbage in world (Salim and Abed 2015). Bearing leafy green heads, the cabbage is used as salad, vegetable, food (cooked/raw), as well as for medicinal purposes (Tripathi 1999; Koza et al. 2018). Rapeseed (*Brassica campestris* L.) and Indian mustard (*Brassica juncea* L. Czern & Coss.) are the major oilseed crops in the world after soybean and groundnut, respectively (Singh et al. 2010; Dutta 2016).

India is one of the largest grower, producer, importer, as well as exporter of these oilseed crops in the world (Barick et al. 2020). The oil content of the rapeseed and mustard ranges about 42% and 38–40%, respectively (Biswas et al. 2019). In southeast Asian countries a complex of more than 30 beneficial and harmful insect pests are found on these crops (Ali and Rizvi 2007; Golizadeh et al. 2009; Kumar et al. 2020; Song et al. 2022). However, genetic breeding and mixed cropping of these crops were conducted for development of improved cultivars with multiple insect pest resistances/tolerances for their better production (Hussain et al. 2020; Roy 2021a; Obermeier et al. 2022).

Among the insect pests, the hairy caterpillar, *Spilarctia obliqua* (Walker, 1855) (Lepidoptera: Arctiidae) (Gupta and Bhattacharya 2008; Warad and Kalleswaraswamy 2017), cabbage caterpillar, *Pieris brassicae* (Linnaeus, 1758) (Lepidoptera: Pieridae) (Ali and Rizvi 2007; Bhowmik and Gupta 2017), and the oligophagous, diamondback moth, *Plutella xylostella* (Linnaeus, 1758) (Lepidoptera: Plutellidae) (Sarfraz et al. 2007; Karmakar et al. 2022) are cosmopolitan in distribution and most serious defoliator of different

✉ Nayan Roy
   nayan909@gmail.com

1 Ecology Research Unit, Department of Zoology, M.U.C. Women's College, Burdwan, West Bengal 713104, India

cruciferous crops. Their full-grown larvae cause severe defoliation and significant reduction in yield (Kumar et al. 2018; Gupta and Bhattacharya 2008). In many countries they have developed resistance to most synthetic insecticides used against them (Sarfraz and Keddie 2005; Hasan and Ansari 2010; Kumar and Ali 2010; Passos et al. 2020). In addition, the indiscriminate use of broad-spectrum insecticides are considered responsible for its high pest status (Aktar et al. 2009; Deguine et al. 2021). Consequently, a comprehensive behavioral study of these pests on most common brassicaceous crops (cabbage, *B. oleracea* L., cv. NS-183, rapeseed, *B. campestris* L. cv. TS 38, and Indian mustard, *B. juncea* L. Czern & Coss., cv. B 85) (Atri et al. 2012; Banerjee et al. 2018; Barick et al. 2020) is needed to promote integrated pest management (IPM) and to reduce the reliance on the chemical pesticides.

Herbivorous insects recognize their host plants by several physicochemical cues (Renwick and Chew 1994; Schoonhoven et al. 2005; Lucas-Barbosa et al. 2016). The first physical contact between an herbivorous insect and host plant occurs on the leaf cuticular surfaces which act as low volatile cues for host acceptance (Chapman and Bernays 1989; Derridj et al. 1996; Jetter and Schäffer 2001; Fernández et al. 2019; Song et al. 2022). Particularly, in lepidopterans it is crucial as their neonates are often relatively immobile and thus depend on the judicious choice of host plant by the adult females (Jetter et al. 2000; Müller and Riederer 2005). Even, the epicuticular waxes protect plant tissues from uncontrolled non-stomatal water loss, UV radiation, defense against pathogens, etc. (Wang et al. 2015). Epicuticular waxes mainly consist of long-chain alkanes, FFAs, esters, aldehydes, and alcohols, which composition varies widely within a species or cultivars of a species (Jetter et al. 2006; Mitra et al. 2020; Debnath et al. 2021). The importance of leaf alkanes and FFAs as semio-chemicals has been demonstrated for management of different insect species (Eigenbrode and Pillai 1998; Müller and Hilker 2001; Das et al. 2019; Little et al. 2019). Specially, low volatile *n*-alkanes and FFAs serve an important role in insect–plant interactions, like olfactory attractant (Roy et al. 2012a, b; Karmakar et al. 2016; Malik et al. 2017) and or oviposition stimulant (van Loon et al. 1992; Parr et al. 1998; Li and Ishikawa 2006). There are a handful of studies that investigated the attraction to host plant volatiles (Ikeura et al. 2010; Feng et al. 2017; Hussain et al. 2020; Song et al. 2022) but unequivocal evidence for host wax chemicals (*n*-alkanes and FFAs) used in olfaction and oviposition site selection by these insect pests has so far been scarce.

In view of the potential for using host-derived semio-chemicals in insect pest management, the aims of this study were (i) to identify and quantify the composition of leaf cuticular wax chemicals (*n*-alkanes and FFAs) present in the three widely used crops (cabbage [cv. NS-183], rapeseed [cv. TS 38], and Indian mustard [cv. B 85]), (ii) to find the role of respective leaf surface (epicuticular) wax chemicals followed by their synthetic analogs and their mixtures (*n*-alkanes and FFAs) in short-range attraction and oviposition of the three pests (*S. obliqua*, *P. brassicae*, and *P. xylostella*) through different bioassay experiments under laboratory conditions, (iii) to find the pattern of olfaction and oviposition preferences of the generalists (moth and butterfly) and specialist (moth) to the wax chemicals, and (iv) to find out the most effective combination of wax chemicals (*n*-alkanes and FFAs) in attraction and oviposition of the pests for designing a baited trap as well as more susceptible crops as trap crop for integrated pest management (IPM) in near future.

Materials and methods

Plants

Three widely used brassicaceous crops, like cabbage, *Brassica oleracea* L. (cv. NS-183), rapeseed, *B. campestris* L. (cv. TS 38), and Indian mustard, *B. juncea* L. (cv. B 85) (Banerjee et al. 2018; Biswas et al. 2019; Barick et al. 2020), were cultivated in a selected field in West Bengal, India (22° 53′ N, 88° 23′ E, 13-m above sea level) during 2020–2021 growing season. Nine plots [each plot 10 m × 10 m; soil organic matter $5.3 \pm 0.2\%$, pH 7.7, average relative humidity (RH) $70 \pm 15\%$, photoperiod 14 L:10 D at 30–36 °C] were prepared for cultivation of the crops with average plant density of 9 ± 3, 34 ± 4, and 40 ± 4 plants/m^2, respectively. The selected crop species were separately germinated and each was grown in three side-by-side plots with a gap of 0.5 m between two plots. A space of 1 m was kept for cultivation of another crop and all plots were maintained without any insecticide spraying. Two to three mature leaves were collected from each 5–7-week-old plant at 6 AM. Three separate batches of around 100-g leaves of each crop (cabbage leaf [$n=7$], rapeseed leaf [$n=51$], and Indian mustard leaf [$n=55$]) were collected from the respective plots for extraction of leaf surface waxes. Only mature leaf surface waxes of crops were considered during this study because the herbivores generally prefer to feed on these leaves.

Insects

Three lepidopteran pests, polyphagous, *S. obliqua* Walker (Arctiidae), *P. brassicae* L. (Pieridae), and oligophagous, *P. xylostella* L. (Plutellidae) adults (males and females), were collected by light trap from the similarly cultivated sesame (*Sesamum indicum*, cv. Rama, Pedaliaceae) plants growing in the field in West Bengal, India and placed them on the same sesame leaves for egg laying. Newly emerged first instar larvae (F$_1$) of each pest species were placed separately

on the same host leaves for feeding and they were kept at 27 ± 1 °C, $70 \pm 10\%$ RH, and 14 L:10 D photoperiod with light intensity of 1500 lx in a Biological Oxygen Demand (BOD) incubator as in Roy (2019b, 2020). Three generations (F_1–F_3) of each pest species were completed on the same host leaves. The F_4 mature females (1–2 days old) of each species were used for olfactory and oviposition bioassays in laboratory conditions. The larvae and adults (females) of *S. obliqua*, *P. brassicae*, and *P. xylostella* were not reared on the selected host plants (cabbage, rapeseed, and Indian mustard) other than sesame based on Hopkins' host-selection principle (Barron 2001) to avoid any biasness to leaf surface waxes of respective crop species during their bioassays.

Extraction of leaf surface wax

Freshly collected mature leaves of about 100 g for each crop (cabbage [cv. NS-183], rapeseed [cv. TS 38], and Indian mustard [cv. B 85]), respectively (ESM Table 1) with three replications were dipped in 2L *n*-hexane separately for 1 min at room temperature for extraction of their surface wax which yielded straw-colored extracts without trace of any chlorophyll (Mitra et al. 2020). The crude extract was passed through Whatman No. 41 (Maidstone, UK) filter paper and was evaporated at room temperature (20–22 °C) to dryness. The extraction was repeated three times separately for each crop and the dry extract (wax) were yielded 16.667 ± 0.371, 38.400 ± 0.519, and 73.067 ± 0.867 mg 100 g^{-1} in cabbage, rapeseed, and Indian mustard leaves, respectively (ESM Table 1). Each crude extract was then dissolved in 30-ml *n*-hexane and divided into three equal portions (equivalent to 33.33 g of leaves), first one used for identification and quantification of *n*-alkanes and FFAs, whereas remaining second and third one after purification used for attraction and oviposition bioassays, respectively. All solvents used were of analytical grade and purchased from E. Merck (Mumbai, India). All standard *n*-alkanes and fatty acids (FAs) (> 99% purity) were purchased from Sigma-Aldrich (Germany).

Table 1 Composition of *n*-alkanes (µg leaf^{-1}) in plant surface waxes (Mean $\pm$ SE, $n = 3$) of three selected brassicaceous crops (cabbage, *Brassica oleracea* L. [cv. NS-183], rapeseed, *B. campestris* L. [cv. TS 38], and Indian mustard, *B. juncea* L. [cv. B 85]) determined during their growing season in 2020–2021

Alkanes (µg leaf^{-1})	Cabbage	Rapeseed	Indian mustard	$F_{2,6}$	P
n-Tetradecane (*n*-C_{14})	4.261 ± 0.113^a	4.647 ± 0.047^b	1.347 ± 0.080^c	457.361	<0.001
n-Pentadecane (*n*-C_{15})	39.944 ± 1.058^a	20.253 ± 0.204^b	12.164 ± 0.724^c	363.463	<0.001
n-Hexadecane (*n*-C_{16})	105.645 ± 2.798^a	76.903 ± 0.775^{bA}	29.691 ± 1.767^c	381.913	<0.001
n-Octadecane (*n*-C_{18})	169.702 ± 4.495^a	105.860 ± 1.067^b	49.860 ± 2.968^c	357.822	<0.001
n-Eicosane (*n*-C_{20})	155.249 ± 4.112^a	98.299 ± 0.991^b	44.610 ± 2.655^c	368.244	<0.001
n-Docosane (*n*-C_{22})	140.145 ± 3.712^a	81.084 ± 0.817^b	34.806 ± 2.072^c	446.351	<0.001
n-Tricosane (*n*-C_{23})	24.728 ± 0.655^a	15.762 ± 0.159^b	2.127 ± 0.127^c	826.376	<0.001
n-Tetracosane (*n*-C_{24})	14.190 ± 0.376^a	23.463 ± 0.236^b	2.333 ± 0.139^c	1554.525	<0.001
n-Pentacosane (*n*-C_{25})	134.964 ± 3.575^a	76.244 ± 0.768^{bA}	28.056 ± 1.670^c	532.276	<0.001
n-Hexacosane (*n*-C_{26})	54.823 ± 1.452^a	26.394 ± 0.266^b	4.817 ± 0.287^c	834.568	<0.001
n-Heptacosane (*n*-C_{27})	107.842 ± 2.856^a	62.660 ± 0.632^b	19.950 ± 1.187^c	581.469	<0.001
n-Octacosane (*n*-C_{28})	48.073 ± 1.273^a	64.653 ± 0.652^b	16.860 ± 1.003^c	578.732	<0.001
n-Nonacosane (*n*-C_{29})	71.758 ± 1.901^a	50.316 ± 0.507^b	15.671 ± 0.933^c	507.014	<0.001
n-Triacontane (*n*-C_{30})	193.154 ± 5.116^a	126.437 ± 1.274^b	32.072 ± 1.909^c	625.086	<0.001
n-Hentriacontane (*n*-C_{31})	65.533 ± 1.736^a	47.634 ± 0.480^b	15.115 ± 0.900^c	483.659	<0.001
n-Dotriacontane (*n*-C_{32}) Branch	–	18.356 ± 0.185^b	6.193 ± 0.369^c	1538.144	<0.001
n-Dotriacontane (*n*-C_{32})	99.128 ± 2.625^a	371.268 ± 3.742^b	100.550 ± 5.984^c	1299.159	<0.001
n-Tritriacontane (*n*-C_{33}) Branch	–	–	0.759 ± 0.045	–	–
n-Tritriacontane (*n*-C_{33})	33.377 ± 0.884^a	82.895 ± 0.836^b	25.941 ± 1.544^{cB}	744.345	<0.001
n-Tetratriacontane (*n*-C_{34}) Branch	–	71.032 ± 0.716^a	26.083 ± 1.552^{bB}	1325.268	<0.001
n-Tetratriacontane (*n*-C_{34})	23.162 ± 0.613^a	709.447 ± 7.151^b	235.751 ± 14.031^c	1490.775	<0.001
n-Pentatriacontane (*n*-C_{35}) Branch	–	7.411 ± 0.075^a	4.832 ± 0.288^b	481.040	<0.001
n-Pentatriacontane (*n*-C_{35})	20.853 ± 0.552^a	95.679 ± 0.964^b	35.925 ± 2.138^c	809.106	<0.001
n-Hexatriacontane (*n*-C_{36}) Branch	–	34.167 ± 0.344^a	14.727 ± 0.877^b	993.512	<0.001
n-Hexatriacontane (*n*-C_{36})	22.667 ± 0.600^a	180.716 ± 1.821^b	75.833 ± 4.513^c	806.833	<0.001

Within rows and columns means followed by same letters (lower and upper case, respectively) are not significantly different ($P \geq 0.05$) by Tukey's HSD test

Analysis of *n*-alkanes

One half of the first portion of each crude extract of each kind of crop (cabbage, rapeseed, and Indian mustard) leaves was passed through a column of aluminum oxide (Alcoa, Frankfurt, Germany: F-20 grade) and eluted with petroleum ether. The eluent was fractioned by thin-layer chromatography (TLC) on silica gel G (Sigma St. Louis, MO, USA) of 0.5 mm thickness using carbon tetrachloride (CCl_4) as the mobile phase. A faint yellowish band was appeared on the TLC plate and the plate was air-dried under laboratory conditions. The R_f (Retention factor) value (0.86) was compared with the R_f value of a mixture of synthetic *n*-alkanes between *n*-C_{10} and *n*-C_{40}. The single hydrocarbon band produced in each TLC plate was eluted from the silica gel layer with chloroform, which showed only C–H stress in IR spectroscopy (JASCO FT-IR spectrophotometer). The purified alkane samples were used for gas chromatography–mass spectrometry (GC–MS) and GC-FID (flame ionization detector) for identification and quantification, respectively, as described by Roy (2019a). The extracts were analyzed with a Shimadzu GCMS-QP5050A to produce electron ionization (EI) mass spectra using HP-5MS column for GCMS-EI analysis using a specified oven temperature program (initially 80 °C held for 2 min, then raised at 15 °C/min to 320 °C, and finally held for 15 min) as described by Roy (2021b). The areas of each peak were converted into quantities of *n*-alkanes based on GC peak area of internal standard heneicosane (*n*-C_{21} at 100 ng μl^{-1}).

Analysis of FFAs

Remaining half of the first portion of each crude extract of each crop (cabbage, rapeseed, and Indian mustard) leaves was mixed with diethyl ether and filtered through Whatman No. 41 filter paper. The extract was purified by TLC on silica gel G of 0.5 mm thickness using *n*-butanol:acetic acid:water (4:1:5) as the mobile phase after discarding water. The band (R_f 0.69) was eluted from the silica gel layer with diethyl ether to get purified FFAs. Then the purified FFAs were esterified with 3-ml BF_3-Methanol followed by warming for 5 min in a hot water bath at 50–60 °C and cooled at room temperature of 20–22 °C. Hexane (40 ml) was added to this mixture followed by washing with saturated NaCl twice in a separating funnel. The aqueous layer of each sample was discarded and the hexane fraction was passed through 40-g anhydrous Na_2SO_4. One portion of each esterified sample was used for GC–MS and another for GC-FID. The extraction of FFAs from each crude extract was separately repeated thrice followed by esterification as described by Roy (2019a). The extracts were analyzed with a Shimadzu GCMS-QP5050A to produce electron ionization (EI) mass spectra using HP-5MS column for GCMS-EI analysis using a specified oven temperature program (initially held at 120 °C for 2 min, then raised at the rate of 10 °C/min to 220 °C, and finally held at 220 °C for 15 min) as described by Roy (2021b). The area of each peak was converted into quantities of FFAs based on GC peak area of internal standard methyl tricosanoate ($C_{23:0}$ at 100 ng μl^{-1}).

Bioassays

Wax chemicals for bioassays

Both natural *n*-alkanes and FFAs isolated from leaf surface wax of the three brassicaceous crops (cabbage, rapeseed, and Indian mustard) were prepared in leaf equivalent (μg leaf^{-1} ml^{-1}) amount dissolving in petroleum ether for different bioassays (olfactory attraction and oviposition) of selected generalists (*S. obliqua* and *P. brassicae*) and specialist (*P. xylostella*) pests through different treatments under defined conditions. Petroleum ether was used as the control solvent because both adults and larvae of the pests were neither attracted nor deterred by it in their preliminary bioassay experiments. The synthetic individual *n*-alkanes, FFAs, and their mixtures mimicking the natural leaf wax (μg leaf^{-1} ml^{-1}) were prepared by the same procedure as in naturally isolated chemicals. The de-waxed leaves for the bioassays were prepared using fresh leaves before dipped in *n*-hexane for 1 min as described in wax extraction process.

Insects for bioassays

Newly emerged (1–2 days old) F_4 mature females of *S. obliqua*, *P. brassicae*, and *P. xylostella* were provisioned with water and starved for 12 h prior to use in olfactory attraction and only 10% sucrose solution provided as food during oviposition bioassays in different treatments. Always healthy individuals were selected and used once throughout the bioassay experiments with three replications for each pest species.

Y-tube olfactometer for bioassays:

The effectiveness of *n*-alkanes and FFAs as olfactory attractants was evaluated by different treatments under specified conditions described below. The behavioral responses of adult females were investigated in a Y-tube olfactometer [20.0-cm long (l) stem and arms, 8.0 cm diameter (d), 60° Y angle] as described by Roy (2019a). The stem of the olfactometer was connected to a porous glass vial [[8.0 cm (d) × 10.0 cm long (l)] in which test insects were released. Each arm of the olfactometer was connected to a glass micro kit adapter [4.0 cm (d) × 6.0 cm (l)] fitted into a glass vial [8.0 cm (d) × 8.0 cm (l)]. The membrane pump producing an air flow of 450 ml min^{-1} was first purified by passing

through charcoal filter and the flow of purified air was adjusted to 150 ml min^{-1} which led into left and right glass vials through the micro kit adapters. All the connections between different parts of the set-up consisted of silicon tube. One ml of solvent bearing one gram leaf equivalent (µg leaf^{-1} ml^{-1}) amount of identified n-alkanes and FFAs were applied (individually or in mixture to Whatman no. 41 filter paper pieces [4 cm^2] or on leaf) as volatile cues and another only with solvent (petroleum ether) or de-waxed leaf as control and allowed to evaporate the solvent in open space (1 min) under laboratory condition. These filter papers or leaves in different treatments were introduced into the glass vials attached with the olfactometer. One adult female of each pest (*S. obliqua*, *P. brassicae*, and *P. xylostella*) was introduced into the porous glass vial attached with the olfactometer to measure the attractiveness.

The behavior of each female was observed for 3 min in the Y-tube because increasing the experimental time did not increase the number of responding insects. A decision line was located at 10 cm in each side from the junction of the Y-tube and an individual crossing the line within 3 min from release with at least half the body was counted as a response. If no line was crossed after the experimental time had run out, the experiment was treated as no response. To eliminate traces from previous trials, the tube was cleaned with petroleum ether followed by acetone and dried before a new individual was tested. Each experiment with one volatile sample was conducted until a total of 72 (24 × 3) females had used and after testing 12 insects the olfactometer set-up and the position of the two arms were systematically changed (rotated 180°) in order to avoid any positional biasness.

Bioassays for host preference by leaf cuticular wax chemicals

The dual-choice tests for olfactory attraction of *S. obliqua*, *P. brassicae*, and *P. xylostella* females to natural n-alkanes, FFAs, and wax in leaf equivalent (µg leaf^{-1}) amount along with intact leaf of selected three crops (cabbage, rapeseed, and Indian mustard) were conducted to find the most preferred crop for them with three replications in four different treatments under defined conditions as follows:

Condition 1 (C1): Normal vs. de-waxed leaf of the selected crops (ESM Table 2).

Condition 2 (C2): Natural n-alkanes treated filter paper vs. solvent (ESM Table 2).

Condition 3 (C3): Natural FFAs treated filter paper vs. solvent (ESM Table 2).

Condition 4 (C4): Natural wax-treated filter paper vs. solvent (ESM Table 2).

The attraction index (AI%) is determined for each pest using the formula $[(T - C)/(T + C) \times 100]$, where T is the number of adults (females) attracted in various treatments (normal leaf or wax chemicals) and C is the number of adults (females) attracted in controls (de-waxed leaf or solvent) with few modifications (Singh et al. 2011).

The same dual-choice olfaction test was conducted for identified n-alkanes and FFAs present in the most preferred host (cabbage, cv. NS-183) individually through their synthetic analogs in leaf equivalent (µg leaf^{-1}) amounts to find the most preferred cues having minimum ≥ 65% attractiveness with three replications under same conditions as in host preference experiments (ESM Table 3). Even, the same tests to the most preferred cues of selected synthetic n-alkanes (n-C$_{16}$, n-C$_{18}$, n-C$_{20}$, n-C$_{22}$, n-C$_{22}$) and FFAs (C$_{12:0}$, C$_{16:0}$, C$_{18:3}$, C$_{18:2}$, and C$_{18:1}$) were conducted in mixture as well as in combination (5 n-alkanes + 5FFAs) under four defined conditions (A1, A2, A3, and A4) with three replications in leaf equivalent (µg leaf^{-1}) amounts of respective wax chemicals present in cabbage (cv. NS-183) because they were produced more attractiveness than their individual cues to the pest species (ESM Table 4).

Female oviposition bioassays

Oviposition preference was assessed using newly emerged 24 pairs of mature male and female of each pest species (*S. obliqua*, *P. brassicae*, and *P. xylostella*) in 3 groups for each (24 × 3 = 72 pairs) in glass chambers (40 × 40 × 40 cm^3) using the synthetic mixtures as in adult olfactory bioassays (ESM Table 4). The dual-choice test was conducted for each treatment in the said glass chambers covered with nylon net and the data were collected after 24-h interval up to 96 h. For the choice experiments, each filter paper or leaf was marked to create two halves vertically. One half was treated with the test compound and the other half was treated with solvent as a control. Each mixture was applied with a micropipette in leaf equivalent (µg leaf^{-1}) amount present in cabbage (cv. NS-183) leaf and after evaporating the solvent, one pair of newly emerged (1–2 days old) F$_4$ mature adults (1:1 sex ratio) was released in each glass chamber. Each chamber was provided with 10% sucrose solution as food and then kept in a BOD incubator as in mass culture. The filter paper or leaf of the three replicates having egg masses was detached from the glass chamber and eggs deposited on the surfaces were counted at the black head stage through five defined conditions (O1, O2, O3, O4, and O5) for each pest as in adult olfactory attraction (ESM Table 4). The oviposition preference index (OPI%) is determined for the conditions using the formula $[(I - D)/(I + D) \times 100]$, where I is the number of eggs laid in various treatments and D is the number of eggs laid in controls with few modifications (Singh et al. 2011).

Data analyses

The data on total amounts of *n*-alkanes and FFAs present in the selected hosts (cabbage, rapeseed, and Indian mustard) were in normal distribution (Kruskal–Wallis's test) and analyzed by one-way ANOVA followed by Tukey's HSD test. The data obtained for responses of the selected pests (*S. obliqua*, *P. brassicae*, and *P. xylostella*) to epicuticular wax compounds and mixtures of their synthetic analogs were analyzed by Chi-square (χ^2) test based on the null hypothesis whether the ratio of individual choosing the stimulus vs. the control differ significantly from 1:1 (Zar 1999). Insects that did not respond to any one of the treatments were excluded from the analyses. All the statistical analyses were conducted using the software SPSS 16.0 (SPSS Inc., Chicago, IL, USA).

Results

Surface wax

A single mature leaf of cabbage, rapeseed, and Indian mustard yielded 7948.586 ± 285.802, 6594.515 ± 393.463, and 1528.106 ± 91.282 µg (mean $\pm$ SE, $n = 3$) surface wax, respectively (ESM Table 1). The extracted waxes from a single leaf of cabbage, rapeseed, and Indian mustard represented 1528.620 ± 40.461, 2451.319 ± 24.708, and 836.034 ± 49.731 µg *n*-alkanes and 481.533 ± 16.555, 558.142 ± 17.809, and 139.019 ± 4.402 µg FFAs, respectively (ESM Table 1). The extracted n-alkanes ($F_{2,6} = 417.324$, $P < 0.001$) and FFAs ($F_{2,6} = 244.713$,

$P < 0.001$) of the selected crops were with significant differences (rapeseed > cabbage > Indian mustard) but total waxes were without significant difference ($F_{2,6} = 1.018$, $P = 0.416$) between the crops (cabbage > rapeseed > Indian mustard) at respective leaf equivalent (µg leaf^{-1}) amount (ESM Table 1).

Alkanes in leaf surface wax

Total 25 different *n*-alkanes (20 straight chain + 5 branch chain) were identified between *n*-C$_{14}$ to *n*-C$_{36}$ and out of them 20, 24, and 25 types of *n*-alkanes were detected from the leaves of cabbage, rapeseed, and Indian mustard, respectively (Table 1). Among them *n*-Triacontane (*n*-C$_{30}$) in cabbage (193.154 ± 5.116 µg leaf^{-1}) and *n*-Tetratriacontane (*n*-C$_{34}$) in rapeseed (709.447 ± 7.151 µg leaf^{-1}) and Indian mustard (235.751 ± 14.031 µg leaf^{-1}) were predominant (Table 1). All the identified *n*-alkanes were differed significantly ($F_{2,6} \geq 357.822$, $P < 0.001$) within the selected crop (cabbage, rapeseed, and Indian mustard) species (Table 1).

FFAs in leaf surface wax

Total 15 different FFAs (11 saturated + 4 unsaturated) were identified between C$_{12:0}$ and C$_{22:0}$ and out of them 15, 12, and 13 types of FFAs were detected from the leaves of cabbage, rapeseed, and Indian mustard, respectively (Table 2). Among them hexadecanoic acid (C$_{16:0}$) in cabbage (130.905 ± 4.468 µg leaf^{-1}) and hexadecenoic acid (C$_{16:1}$) in rapeseed (220.401 ± 7.199 µg leaf^{-1}) and Indian mustard (71.969 ± 2.296 µg leaf^{-1}) were predominant (Table 2). All the identified FFAs were differed significantly

Table 2 Composition of free fatty acids (FFAs) (µg leaf^{-1}) in plant surface waxes (Mean $\pm$ SE, $n = 3$) of three selected brassicaceous crops (cabbage, *Brassica oleracea* L. [cv. NS-183], rapeseed, *B. campestris* L. [cv. TS 38], and Indian mustard, *B. juncea* L. [cv. B 85]) determined during their growing season in 2020–2021

Free fatty acids (µg leaf^{-1})	Cabbage	Rapeseed	Indian mustard	$F_{2,6}$	P
Dodecanoic acid (C$_{12:0}$)	70.587 ± 2.409^a	2.195 ± 0.072^b	1.684 ± 0.054^c	810.816	< 0.001
Tridecanoic acid (C$_{13:0}$)	26.297 ± 0.898^a	7.895 ± 0.258^b	2.512 ± 0.080^c	531.225	< 0.001
Tetradecanoic acid (C$_{14:0}$)	7.772 ± 0.265^a	28.503 ± 0.931^b	4.909 ± 0.157^c	517.202	< 0.001
Pentadecanoic acid (C$_{15:0}$)	3.418 ± 0.117^{aA}	36.694 ± 1.198^b	4.084 ± 0.130^c	740.031	< 0.001
Hexadecenoic acid (C$_{16:1}$)	41.726 ± 1.424^a	220.401 ± 7.199^b	71.969 ± 2.296^c	464.060	< 0.001
Hexadecanoic acid (C$_{16:0}$)	130.905 ± 4.468^a	29.559 ± 0.965^b	9.675 ± 0.309^c	604.190	< 0.001
Heptadecanoic acid (C$_{17:0}$)	3.468 ± 0.118^{aA}	14.122 ± 0.461^b	0.277 ± 0.009^c	695.151	< 0.001
Octadecatrienoic acid (C$_{18:3}$)	36.865 ± 1.258	–	–	–	–
Octadecadienoic acid (C$_{18:2}$)	47.131 ± 1.609	–	–	–	–
Octadecenoic acid (C$_{18:1}$)	75.757 ± 2.586^a	–	2.512 ± 0.080^b	830.114	< 0.001
Octadecanoic acid (C$_{18:0}$)	19.743 ± 0.674^a	27.103 ± 0.885^b	4.675 ± 0.149^c	311.209	< 0.001
Nonadecanoic acid (C$_{19:0}$)	2.079 ± 0.071^a	37.256 ± 1.217^b	5.933 ± 0.189^c	733.917	< 0.001
Eicosanoic acid (C$_{20:0}$)	1.511 ± 0.052^{aB}	25.738 ± 0.841^b	4.193 ± 0.134^c	727.665	< 0.001
Heneicosanoic acid (C$_{21:0}$)	1.467 ± 0.050^{aB}	21.235 ± 0.694^b	1.942 ± 0.062^c	782.990	< 0.001
Docosanoic acid (C$_{22:0}$)	12.943 ± 0.442^a	107.245 ± 3.503^b	24.694 ± 0.788^c	605.472	< 0.001

Within rows and columns means followed by same letters (lower and upper case, respectively) are not significantly different ($P \geq 0.05$) by Tukey's HSD test

$(F_{1,4} \geq 311.209, P < 0.001)$ within the selected crop (cabbage, rapeseed, and Indian mustard) species (Table 2).

Adult olfactory attractions

A series of olfactory bioassays were conducted to find the attractiveness (AI%) of *S. obliqua*, *P. brassicae*, and *P. xylostella* (females) toward leaf cuticular wax chemicals (*n*-alkanes and FFAs) of selected crop (cabbage, rapeseed, and Indian mustard) species, their synthetic individuals, and mixture of most attractive individual wax chemicals in leaf equivalent (μg leaf^{-1}) amount (ESM Tables 2, 3 and 4, Figs. 1, 2, 3).

In host preference test highest AI (%) of 45.370 ± 2.006, 45.341 ± 2.019, and $42.593 \pm 2.045\%$, respectively, in *S. obliqua*, *P. brassicae* and *P. xylostella* were found toward the natural wax of cabbage leaf (7948.586 ± 285.802 μg leaf^{-1}) which might be due to higher wax content followed by rapeseed and Indian mustard, respectively (ESM Table 2, Fig. 1). The degree of attractiveness (AI%) toward the conditions can be arranged in the order of natural wax (C4) > intact leaf (C1) > FFAs (C3) > *n*-alkanes (C2) for the pests (*S. obliqua* > *P. brassicae* > *P. xylostella*) (ESM Table 2, Fig. 1). The attraction (%) toward any treatments over controls were always significantly ($\chi^2 \geq 3.874$, df = 1, $P < 0.05$) higher in all conditions for each pest species (ESM Table 2). The AI (%) values of the pests were significantly ($F_{2,6} \geq 7.737$, $P \leq 0.022$) differed except C2 and C3 for *S. obliqua* and *P.*

xylostella, respectively, within the crop (cabbage > rapeseed > Indian mustard) species (ESM Table 2, Fig. 1).

To find most effective synthetic wax chemicals highest AI (%) was observed toward *n*-hexadecane (*n*-C$_{16}$) and dodecenoic acid (C$_{12:0}$) as 39.815 ± 2.578 and $43.981 \pm 2.598\%$, respectively, in *P. xylostella* (ESM Table 3, Fig. 2). Among the treatments the most preferred wax chemicals were consisted of FFAs (C$_{12:0}$, C$_{16:0}$, C$_{18:3}$, C$_{18:2}$, C$_{18:1}$) > *n*-alkanes (*n*-C$_{16}$, *n*-C$_{18}$, *n*-C$_{20}$, and *n*-C$_{22}$, *n*-C$_{30}$) for the three pests (*S. obliqua*, *P. brassicae*, and *P. xylostella*) over the other (ESM Table 3, Fig. 2). The attraction (%) toward individual wax chemicals over controls were always significantly ($\chi^2 \geq 6.958$, df = 1, $P < 0.05$) higher for each pest species except *n*-Triacontane (*n*-C$_{30}$) ($\chi^2 = 3.032$, df = 1, $P > 0.05$) in *P. xylostella* (ESM Table 3). Similarly, all the AI (%) values of selected pests were without significant differences ($F_{2,6} \leq 4.742$, $P \geq 0.058$) for the most preferred wax chemicals except *n*-Triacontane (*n*-C$_{30}$) ($F_{2,6} = 7.842$, $P = 0.020$) within the pests (ESM Table 3, Fig. 2).

During olfaction toward most effective wax chemicals, the highest AI (%) of 46.759 ± 2.377, 52.315 ± 2.457, and $49.537 \pm 2.454\%$, respectively, in *S. obliqua*, *P. brassicae*, and *P. xylostella* were found toward the combined synthetic mixture (5 *n*-alkanes [*n*-C$_{16}$, *n*-C$_{18}$, *n*-C$_{20}$, *n*-C$_{22}$, *n*-C$_{30}$] + 5 FFAs [C$_{12:0}$, C$_{16:0}$, C$_{18:3}$, C$_{18:2}$, and C$_{18:1}$])-treated leaf (A4) of cabbage (9073.726 ± 84.235 μg leaf^{-1}) due to higher amount of wax chemicals followed by combined synthetic mixture-treated filter paper (A3), combined synthetic mixture of

Fig. 1 Adult olfactory attraction (Mean ± SE, *n* = 72) of three lepidopteran pests, polyphagous, *S. obliqua* Walker (Arctiidae), *P. brassicae* L. (Pieridae), and oligophagous, *P. xylostella* L. (Plutellidae) to plant surface wax chemicals (*n*-alkanes and FFAs in leaf equivalent amount [μg leaf^{-1}]) of three selected host (cabbage, *B. oleracea* L. [cv. NS-183], rapeseed, *B. campestris* L. [cv. TS 38], and Indian mustard, *B. juncea* L. [cv. B 85]), plants under specified bioassay conditions. Means followed by same letters above the error bars are not significantly different ($P \geq 0.05$) by Tukey's HSD test. Where, *C1* intact leaf vs. de-waxed leaf, *C2* natural *n*-alkanes treated filter paper vs. solvent, *C3* natural free fatty acids (FFAs) treated filter paper vs. solvent, *C4* natural wax-treated filter paper vs. solvent, *AI* Attraction index
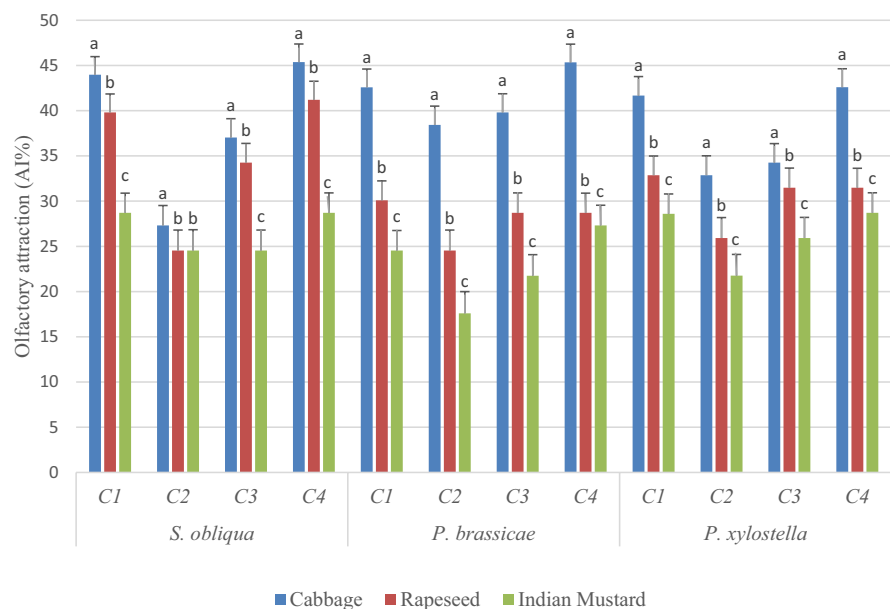
Note: Means followed by same letters above the error bars are not significantly different ($P \geq 0.05$) by Tukey's HSD test. Where, C1: Intact leaf vs. de-waxed leaf, C2: Natural n-alkanes treated filter paper vs. solvent, C3: Natural free fatty acids (FFAs) treated filter paper vs. solvent, C4: Natural wax treated filter paper vs. solvent, AI=Attraction index.

Fig. 2 Adult olfactory attraction (Mean ± SE, $n = 72$) of three lepidopteran pests, polyphagous, *S. obliqua* Walker (Arctiidae), *P. brassicae* L. (Pieridae), and oligophagous, *P. xylostella* L. (Plutellidae) to plant surface wax chemicals (*n*-alkanes and FFAs in leaf equivalent amount [µg leaf^{-1}]) of most preferred host (cabbage, *B. oleracea* L. [cv. NS-183) plants under specified bioassay conditions having more than 65% responses. Means followed by same letters above the error bars are not significantly different ($P \geq 0.05$) by Tukey's HSD test. *AI* Attraction index
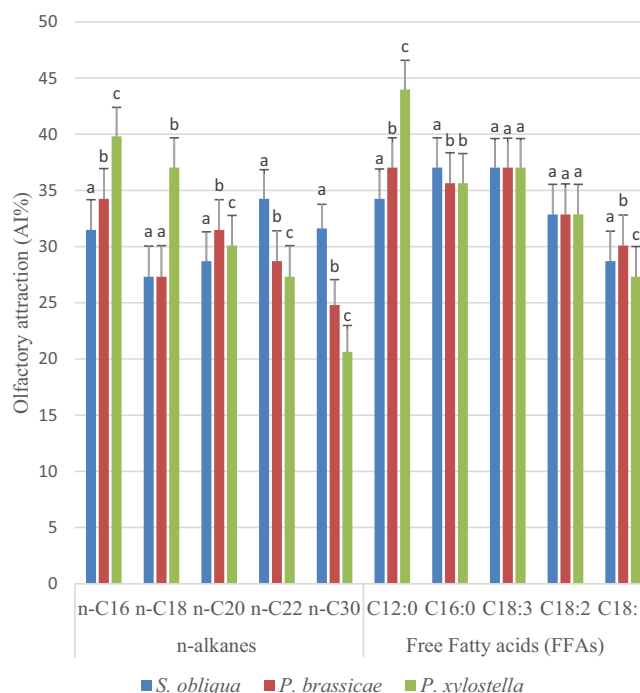
Note: Means followed by same letters above the error bars are not significantly different ($P \geq 0.05$) by Tukey's HSD test. AI=Attraction index.

FFAs (A2), and combined synthetic mixture of *n*-alkanes (A1), respectively (ESM Table 4, Fig. 3). The attraction (%) toward any treatment over controls were always significantly ($\chi^2 \geq 7.980$, df = 1, $P < 0.05$) higher for the pests (ESM Table 4). All the AI (%) values were without significant ($F_{2,6} \leq 4.742$, $P \geq 0.058$) differences within the pests (ESM Table 4). In all the treatments AI (%) values for the pests were in the order of *P. brassicae* > *P. xylostella* > *S. obliqua* and in Tukey's HSD test they were with different significant variations (ESM Table 4, Fig. 3).

Oviposition toward most effective wax chemicals

Highest OPI (%) of 10.185 ± 1.234, 12.963 ± 1.979, and 15.741 ± 1.607%, respectively, in *S. obliqua*, *P. brassicae*, and *P. xylostella* were found toward the combined synthetic mixture (5 *n*-alkanes + 5 FFAs)-treated leaf (O5) of cabbage (9073.726 ± 84.235 µg leaf^{-1}) due to higher amount of wax chemicals followed by combined synthetic mixture-treated filter paper (O4), intact leaf (O1), combined synthetic mixture of FFAs (O3), and combined synthetic mixture of *n*-alkanes (O2), respectively (ESM Table 4, Fig. 3). The oviposition choice (%) toward any treatments over controls was always significantly ($\chi^2 \leq 3.586$, df = 1, $P < 0.05$) lower except O4 and O5 in *P. xylostella* (ESM Table 4). All the OPI (%) values were without any significant ($F_{2,6} \leq 2.769$, $P \geq 0.141$) differences within the pests as they were all
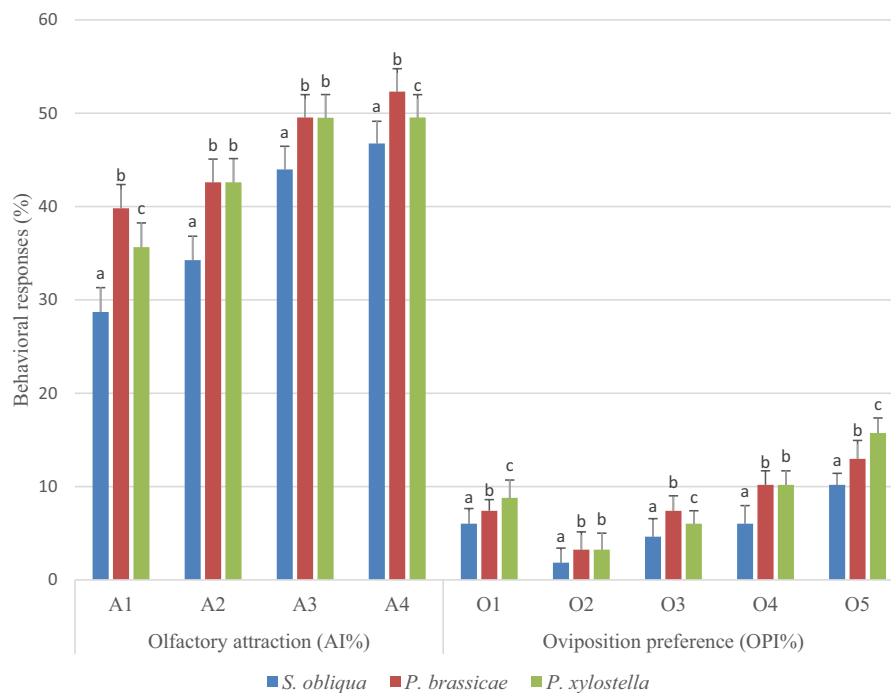
potent pest on cabbage (ESM Table 4). In all the treatments OPI (%) values for the pests were in the order of *P. xylostella* > *P. brassicae* > *S. obliqua* and in Tukey's HSD test they were also with different significant variations (ESM Table 4, Fig. 3).

Discussion

The epicuticular wax of cabbage, rapeseed, and Indian mustard led through different sensory cues to suitable and differently preferred host selection and oviposition in the polyphagous, *S. obliqua*, *P. brassicae*, and oligophagous, *P. xylostella*, pests like the generalist pests, *Diacrisia casignetum*, *Spilosoma obliqua*, *Helicoverpa armigera*, and *Spodoptera litura* (Roy and Barik 2012, 2014; Roy 2019a, 2021b). Total 25 *n*-alkanes from *n*-C$_{14}$ to *n*-C$_{36}$ and 15 FFAs from C$_{12:0}$ to C$_{22:0}$ were detected in leaf epicuticular wax of the three crops as major components with significant variations in their respective quantities (µg leaf^{-1}) as in other plants (Mukherjee et al. 2014, 2015; Mitra et al 2017; Das et al. 2019). Among the identified *n*-alkanes and FFAs, *n*-C$_{34}$ and C$_{16:1}$, respectively, of rapeseed leaf were most predominant.

Similarly, 9 *n*-alkanes (*n*-C$_{24}$ to *n*-C$_{30}$, *n*-C$_{32}$, and *n*-C$_{33}$) and 13 FFAs (C$_{12:0}$ to C$_{20:0}$) were detected in the epicuticular wax of mature leaves of sunflower (*H. annuus* cv. PAC-36), where *n*-C$_{29}$ and C$_{18:2}$, respectively, were most predominant

Fig. 3 Olfactory attraction and oviposition preference (Mean ± SE, $n=72$) of three lepidopteran pests, polyphagous, *S. obliqua* Walker (Arctiidae), *P. brassicae* L. (Pieridae), and oligophagous, *P. xylostella* L. (Plutellidae) to plant surface wax chemicals (*n*-alkanes and FFAs in leaf equivalent amount [µg leaf^{-1}]) of most preferred host (cabbage, *B. oleracea* L. [cv. NS-183) plants under specified bioassay conditions. Means followed by same letters above the error bars are not significantly different ($P \geq 0.05$) by Tukey's HSD test. Where, *A1* synthetic *n*-alkanes treated filter paper vs. solvent, *A2* synthetic free

fatty acids (FFAs) treated filter paper vs. solvent, *A3* combined synthetic mixture-treated filter paper vs. solvent, *A4* combined synthetic mixture-treated intact leaf vs. solvent, *O1* intact leaf vs. de-waxed leaf, *O2* synthetic *n*-alkanes treated filter paper vs. solvent, *O3* synthetic free fatty acids (FFAs) treated filter paper vs. solvent, *O4* combined synthetic mixture-treated filter paper vs. solvent, *O5* combined synthetic mixture-treated intact leaf vs. solvent, *AI* attraction index, *OPI* oviposition preference index

(Roy and Barik 2012, 2014). Eighteen *n*-alkanes (*n*-C$_{16}$ to *n*-C$_{36}$) and 13 FFAs (C$_{12:0}$ to C$_{20:0}$) were detected in the leaf surface wax of jute (*C. capsularis* cv. Sonali [JRC-321]) and among them *n*-C$_{29}$ and C$_{18:1}$, respectively, were most abundant (Roy 2019a). Further, 18 *n*-alkanes (*n*-C$_{15}$ to *n*-C$_{36}$) and 14 FFAs (C$_{12:0}$ to C$_{22:0}$) were detected in the leaf surface wax of grass pea *Lathyrus sativus*, and, among them, *n*-C$_{15}$ and C$_{15:0}$, C$_{16:1}$, respectively, were most predominant (Mitra et al. 2020). Twenty *n*-alkanes (*n*-C$_{15}$ to *n*-C$_{36}$) and 13 FFAs (C$_{12:0}$ to C$_{21:0}$) were identified from green gram *V. radiata* leaves, and, among them, *n*-C$_{25}$ and C$_{16:1}$ and C$_{21:0}$, respectively, were most abundant (Mobarak et al. 2020). Twenty *n*-alkanes from *n*-C$_{14}$ to *n*-C$_{36}$ and 13 FFAs from C12:0 to C21:0 was detected in the leaf surface waxes of three *Trichosanthes anguina* L. cultivars (MNSR-1,

Baruipur Long, and Polo No.1) and among them *n*-C17 and C18:0 were predominant (Debnath et al. 2021). Cuticular wax of sesame (*Sesamum indicum*) cultivars (Savitri and Nirmala) indicated the presence of 14 *n*-alkanes from *n*-C9 to *n*-C44 and 12 FFAs from C9:0 to C20:0, where *n*-C26 and C18:1 were most predominant (Roy 2021b). The above-mentioned *n*-alkanes and FFAs can act as short-range attractants for different insect pests to respective host plants (Li and Ishikawa 2006; Malik et al. 2017; Das et al. 2019; Zhu et al. 2021).

Moreover, there are several behavioral studies only on *P. xylostella* other than *P. brassicae* and *S. obliqua* in specific host selection for alternative management strategies (Wee 2016). Host plant-mediated orientation and oviposition by *P. xylostella* were significantly greater on cabbage,

(*B. oleracea* L. subsp. *capitata*) followed by cauliflower (*B. oleracea* L. subsp. *botrytis*), kohlrabi (*B. oleracea* L. subsp. *gongylodes*), and broccoli (*B. oleracea* L. subsp. *italica*) and female oviposition was significantly greater on injured plant leaves than on intact plants leaves (Reddy et al. 2004). Adult *P. xylostella* were equally attracted to transgenic and nontransgenic cabbage plants but larvae were attracted to transgenic plant and suffered heavy mortality (Kumar 2004). The relative roles of olfaction and vision of *P. xylostella* were regulated by plant volatile cues (Couty et al. 2006). Both sexes of *P. xylostella* responded to leaf volatiles of Oriental mustard, *B. juncea* Cosson, and females laid more eggs for the cues (Pivnick et al. 1990). Whereas, *P. brassicae* elicited oviposition-induced plant volatiles having indirect plant defense cues (Fatouros et al. 2015). The electrophysiological and behavioral responses of *P. xylostella*-mated females showed the repellence for five volatile components like myrcene, γ-terpinene, linalool, camphor, and terpinen-4-ol present in none-host geranium plants (Song et al. 2022). The most active green leaf volatile (GLV), (Z)-3-hexenyl acetate, from *B. oleracea* subsp. *capitata* L. enhances attraction to both males and females of *P. xylostella* to the baited traps with pheromone in 1:1 ratio (Reddy and Guerrero 2000). Even, *P. xylostella*-damaged cabbages emitted herbivore-induced volatile compounds like homoterpene (*E*)-4,8-dimethyl-1,3,7-nonatriene, sesquiterpene (*E*, *E*)-α-farnesene, and (Z)-3-hexenyl acetate and attract their natural enemies for indirect defense of the plants (Vuorinen et al. 2004). Biogenic amines like octopamine and its receptors are involved in mating-triggered oviposition in *P. xylostella* and provide a new strategy for their control (Li et al. 2020). Even, pheromone traps may be a viable alternative to manage *P. xylostella* in an IPM system (Shakeel et al. 2017; Deguine et al. 2021; Passos et al. 2020).

The present study revealed clear olfactory responses of all the pests to *n*-alkanes and FFAs present in leaf cuticular waxes of the selected crops. After reaching within a close range to the host plant, *n*-alkanes and FFAs were acted as a short-range attractant which facilitated oviposition induction in all gravid females. Even, the role of olfaction is well documented in moths due to their typical nocturnal lifestyle (Cunningham et al. 1999). Visual (Barragán-Fonseca et al. 2020), olfactory (Lucas-Barbosa et al. 2016; Das et al. 2019), tactile (Foster and Howard 1998), and gustatory (Feng et al. 2017) cues can themselves or in combinations with each other enhanced behaviors in host selection for oviposition as well as for larval feeding (Carlsson et al. 1999; Bandoly et al. 2015). Although, resistant cabbage (NY 8329) with glossy leaves having triterpenols α- and β-amyrin in the waxes reduced acceptance of the neonate *P. xylostella* (Eigenbrode et al. 1991). But, the synergistic effect of sinigrin (10–3, 10–4, and 10–5 M) with *n*-alkanes on *P. xylostella* oviposition behavior was increased by

additional time spend in contact with the stimuli (Spencer et al. 1999). In this study, olfaction (AI%) toward the natural wax (*n*-alkanes and FFAs) for the pests were in the order of *S. obliqua* > *P. brassicae* > *P. xylostella* within the crop (cabbage > rapeseed > Indian mustard) species. The most preferred wax chemicals were consisted of 5 *n*-alkanes (*n*-C_{16}, *n*-C_{18}, *n*-C_{20}, *n*-C_{22}, and *n*-C_{30}) and 5 FFAs ($C_{12:0}$, $C_{16:0}$, $C_{18:3}$, and $C_{18:2}$, $C_{18:1}$) for the pests. All the AI (%) values of selected pests were without significant differences for the most preferred wax chemicals due to the abundance of host chemicals and preference for the respective hosts as in other pest species (Li and Ishikawa 2006; Mitra et al. 2019). Highest AI (%) in the order of *P. brassicae* > *P. xylostella* > *S. obliqua* was found toward the combined synthetic mixture (5 *n*-alkanes + 5 FFAs)-treated leaf of cabbage due to higher amount of wax chemicals, like other lepidopteran species (Mitra et al. 2020; Mobarak et al. 2020). Similarly, highest OPI (%) was also found toward the same combined synthetic mixture (5 *n*-alkanes + 5 FFAs)-treated leaf of cabbage due to higher amount of wax chemicals as in other pest species (Roy 2019a, 2021b). All the OPI (%) values were without any significant differences within the pests (*P. xylostella* > *P. brassicae* > *S. obliqua*) as they were all potent pest on cabbage. They probably use visual (color and shape), olfactory (odorous *n*-alkanes and FFAs), tactile (surface ultrastructure), and gustatory (cuticular wax) cues in synergistic manner for oviposition preference toward cabbage leaf-like other insects (Mitra et al. 2017; Das et al. 2019; Spencer et al. 1999).

Similarly, 5 long-chain *n*-alkanes (*n*-C_{26} to *n*-C_{30}) of *Zea mays* L. (Poaceae) and *Fallopia japonica* (Houtt.) Ronse Decr. (Polygonaceae) leaves act as oviposition stimulants in the European corn borer *Ostrinia nubilalis* (Hübner) (Lepidoptera: Pyralidae) (Udayagiri and Mason 1997; Li and Ishikawa 2006). Further, two FFAs ($C_{18:1}$, $C_{18:2}$) act as host finding and oviposition cues for *Amyelois transitella* (Walker) (Lepidoptera: Pyralidae) (Phelan et al. 1991). Fatty acids from $C_{8:0}$ to $C_{12:0}$, $C_{18:1}$, and $C_{18:2}$ of *Picea* spp. and *Abies* spp. serve as oviposition stimulants for the *Choristoneura fumiferana* (Clemens) (Lepidoptera, Tortricidae) (Grant et al. 2000). Five predominant *n*-alkanes (*n*-C_{18}, *n*-C_{23}, *n*-C_{24}, *n*-C_{28}, and *n*-C_{32}) and 6 FFAs ($C_{16:0}$, $C_{16:1}$, $C_{18:0}$, $C_{18:1}$, $C_{18:2}$, and $C_{18:3}$) of sunflower-leaf attracted *D. casignetum* (Roy and Barik 2012, 2014). The synthetic combination mixture of 4 *n*-alkanes (*n*-C_{17}, *n*-C_{18}, *n*-C_{27}, and *n*-C_{29}) and 5 FFAs ($C_{16:0}$, $C_{16:1}$, $C_{18:1}$, $C_{18:2}$, and $C_{18:3}$) was most attractive to *D. casignetum* adults, whereas the same mixture excluding 2 *n*-alkanes (*n*-C_{27}, *n*-C_{29}) also caused a significant oviposition preference in jute leaf equivalent amount (Roy 2019a). In the grass pea, 5 *n*-alkanes (*n*-C_{15}, *n*-C_{22}, *n*-C_{25}, *n*-C_{27}, and *n*-C_{33}) and 2 FFAs ($C_{13:0}$, $C_{18:2}$) in mixture acted as attractants and stimulated the emergence of nymphs in *Aphis craccivora* Koch (Hemiptera: Aphididae) at leaf

equivalent amount (Mitra et al. 2020). In green gram (cv. PDM), 4 *n*-alkanes (*n*-C$_{25}$, *n*-C$_{27}$, *n*-C$_{29}$, and *n*-C$_{36}$) and 3 FFAs (C$_{16:1}$, C$_{18:0}$, and C$_{18:3}$) in combination acted as short-range attractants and oviposition stimulants in females of *S. obliqua* at leaf equivalent amount (Mobarak et al. 2020). A synthetic blend of *n*-C17, *n*-C20, *n*-C26, and C18:0 in one leaf equivalent surface wax of *Trichosanthes anguina* L. (cv. MNSR-1) was acted short-range attractants and oviposition stimulants in *Diaphania indica* (Debnath et al. 2021). The olfactory attraction, oviposition, and feeding preference of 3 generalist pests (*S. obliqua* Walker, *H. armigera* Hübner, and *S. litura* Fabricius) were maximum toward 4 *n*-alkanes (*n*-C16, *n*-C22, *n*-C24, and *n*-C26) and 3 FFAs (C12:0, C14:0, and C18:1) mixture in leaf equivalent amount of sesame (cv. Savitri) cultivar (Roy 2021b).

In this study, the pests (*P. brassicae* > *P. xylostella* > *S. obliqua*) were mostly attracted toward the synthetic blend of 5 *n*-alkanes (*n*-C$_{16}$, *n*-C$_{18}$, *n*-C$_{20}$, *n*-C$_{22}$, and *n*-C$_{30}$) and 5 FFAs (C$_{12:0}$, C$_{16:0}$, C$_{18:3}$, C$_{18:2}$, and C$_{18:1}$) present in the leaf equivalent amount (μg leaf^{-1}) of the selected cabbage cultivar. Whereas, the oviposition preference of the pests was in the order of *P. xylostella* > *P. brassicae* > *S. obliqua* due to large amount of wax chemicals along with other physicochemical properties of cabbage leaf which act in synergistic manner as in other studies (Spencer et al.1999). The specialist (*P. xylostella*) moth has more sensitivity to the leaf cuticular wax chemicals in oviposition site selection than the specialists (*P. brassicae* > *S. obliqua*), like other pests (Akhtar and Isman 2003). Whereas, generalist butterfly (*P. brassicae*) has leaf wax chemical guided more olfaction response than the generalist (*S. obliqua*) and specialist (*P. xylostella*) moths as found in other pests (Pivnick et al. 1994; Schäpers et al. 2015). In other instances, host finding and oviposition site selection require a set of sensory (visual, olfactory, tactile, and gustatory) cues that interact with the females before laying eggs (Dahanukar et al. 2005; Renwick and Chew 1994). Host plant selection for oviposition by the females is a decisive step as they require unique set of recognition cues for suitable host selection in establishing a new generation (Schäpers et al. 2015). The preference–performance hypothesis (PPH) or 'mother-knows-best' hypothesis similarly state that natural selection favors those insect females which prefer host plants where the offspring performs best, especially when immature stages are less mobile than adults (Altesor and González 2018; Birke and Aluja 2018). Thus, this finding can explain the clue how mature females of the specialist and generalist pests choose their oviposition site in a perfect fashion for their potential hosts through different sensory modalities for better survival and growth of their neonates, like other insects (Griese et al. 2020; Gripenberg et al. 2010). The females of the selected pests

maximize their own fitness by laying eggs on their preferred crop cultivar (cabbage [cv. NS-183] > rapeseed [cv. TS 38] > Indian mustard [cv. B 85]) where their neonates perform best like other butterflies and moths (Birke and Aluja 2018; Mobarak et al. 2020). So, it can be generalized that both generalist (moth and butterfly) and specialist (moth) have same pattern of olfaction and oviposition preferences with different magnitude of responses. Further, insect herbivores often have higher densities on host plants grown in monocultures than those in diverse environments. Population of *P. xylostella* significantly decreased in a mixed cropping field of *Brassica* spp. due to reduced oviposition compared with a monoculture (Huang et al. 2014). To control *P. xylostella*, the use of intercropping (such as trap crops) is gaining attention as ecologically safe strategy (Hussain et al. 2020). Thus, this study also suggested that the synthetic blends of the 5 *n*-alkanes and 5 FFAs along with the green leaf volatiles (need to determine) of the most preferred cultivar of cabbage (cv. NS-183) can be used as lure to develop baited trap and less preferred crops (rapeseed and Indian Mustard) can be used as main crop with the cabbage as trap crop against the pests for their sustainable ecological management in near future.

Declarations

References

Akhtar Y, Isman MB (2003) Larval exposure to oviposition deterrents alters sub-sequent oviposition behavior in generalist, *Trichoplusia ni* and specialist, *Plutella xylostella* moths. J Chem Ecol 29:1853–1870. https://doi.org/10.1023/A:1024802328458

Aktar MW, Sengupta D, Chowdhury A (2009) Impact of pesticides use in agriculture: their benefits and hazards. Interdiscip Toxicol 2:1–12. https://doi.org/10.2478/v10102-009-0001-7

Ali A, Rizvi PQ (2007) Development response of cabbage butterfly, *Pieris brassicae* L. on different cole crops under laboratory and field conditions. Asian J Plant Sci 6:1241–1245. https://doi.org/10.3923/ajps.2007.1241.1245

Altesor P, González A (2018) Preference–performance in a specialist sawfly on congeneric host plants. Entomol Exp Appl 166:1–10. https://doi.org/10.1111/eea.12690

Atri C, Kumar B, Kumar H, Kumar S, Sharma S (2012) Banga SS (2012) Development and characterization of *Brassica juncea* – fruticulosa introgression lines exhibiting resistance to mustard aphid (*Lipaphis erysimi* Kalt). BMC Genet 13:104. https://doi.org/10.1186/1471-2156-13-104

Bandoly M, Hilker M, Steppuhn A (2015) Oviposition by *Spodoptera exigua* on *Nicotiana attenuata* primes induced plant defense against larval herbivory. Plant J 83:661–672. https://doi.org/10.1111/tpj.12918

Banerjee H, Samanta S, Dutta A, Sarkar S, Garai S (2018) Selection of rapeseed-mustard varieties in coastal region of West Bengal: a way forward to rice-fallow intensification. J Indian Soc Coastal Agric Res 36:54–63

Barick BB, Patra BC, Bandyopadhyay P (2020) Performance of rapeseed (*Brassica campestris* L.) under varied irrigation and sowing methods. J Crop Weed 16:269–273. https://doi.org/10.22271/09746315.2020.v16.i2.1349

Barragán-Fonseca KY, van Loon JJA, Dicke M, Lucas-Barbosa D (2020) Use of visual and olfactory cues of flowers of two brassicaceous species by insect pollinators. Ecol Entomol 45:45–55. https://doi.org/10.1111/een.12775

Barron AB (2001) The life and death of Hopkins' host-selection principle. J Insect Behav 14:725–737. https://doi.org/10.1023/A:1013033332535

Bhowmik M, Gupta M (2017) Biology of cabbage butterfly *Pieris brassicae* Linn. (Lepidoptera: Pieridae). Int J Curr Microbiol Appl Sci 6:3639–3644

Birke A, Aluja M (2018) Do mothers really know best? Complexities in testing the preference-performance hypothesis in polyphagous frugivorous fruit flies. Bull Entomol Res 108:674–684. https://doi.org/10.1017/s0007485317001213

Biswas S, Mukherjee B, Munshi A, Chongre S, Ray M (2019) Evaluation of mustard hybrid varieties in gangetic plains of West Bengal, India. Int J Curr Microbiol App Sci 8:585–590. https://doi.org/10.20546/ijcmas.2019.810.065

Carlsson MA, Anderson P, Hartlieb E, Hansson BS (1999) Experience-dependent modification of orientational response to olfactory cues in larvae of *Spodoptera littoralis*. J Chem Ecol 25:2445–2454. https://doi.org/10.1023/A:1020865922827

Chapman RF, Bernays EA (1989) Insect behavior at the leaf surface and learning as aspects of host plant selection. Cell Mol Life Sci 45:215–222

Couty A, Emden HV, Perry JN, Hardie JIM, Pickett JA, Wadhams LJ (2006) The roles of olfaction and vision in host-plant finding by the diamondback moth, *Plutella xylostella*. Physiol Entomol 31:134–145. https://doi.org/10.1111/j.1365-3032.2006.00499.x

Cunningham JP, Zalucki MP, West SA (1999) Learning in *Helicoverpa armigera* (Lepidoptera: Noctuidae): a new look at the behavior and control of a polyphagous pest. Bull Entomol Res 89:201–207. https://doi.org/10.1017/s0007485399000310

Dahanukar A, Hallen EA, Carlson JR (2005) Insect chemoreception. Curr Opin Neurobiol 15:423–430. https://doi.org/10.1016/j.conb.2005.06.001

Das S, Koner A, Barik A (2019) A beetle biocontrol agent of rice field weeds recognizes its host plants by surface wax long-chain alkanes and free fatty acids. Chemoecology 29:155–170. https://doi.org/10.1007/s00049-019-00285-1

Debnath R, Mitra P, Das S, Barik A (2021) Leaf surface wax chemicals in *Trichosanthes anguina* (Cucurbitaceae) cultivars mediating short-range attraction and oviposition in *Diaphania indica*. J Chem Ecol 47:664–679. https://doi.org/10.1007/s10886-021-01291-w

Deguine JP, Aubertot JN, Flor RJ, Lescourret F, Wyckhuys KAG, Ratnadass A (2021) Integrated pest management: good intentions, hard realities a review. Agron Sustain Dev 41:38. https://doi.org/10.1007/s13593-021-00689-w

Derridj S, Wu B, Stammitti L, Garrec J, Derrien A (1996) Chemicals on the leaf surface, information about the plant available to insects. Entomol Exp Appl 80:197–201. https://doi.org/10.1111/j.1570-7458.1996.tb00917.x

Dutta A (2016) Impact of improved technologies on productivity and profitability of rapeseed mustard production at farm level in West Bengal, India. SAARC J Agric 14:126–136. https://doi.org/10.3329/sja.v14i2.31251

Eigenbrode SD, Pillai SK (1998) Neonate *Plutella xylostella* responses to surface wax components of a resistant cabbage (*Brassica oleracea*). J Chem Ecol 24:1611–1627. https://doi.org/10.1023/A:1020812411015

Eigenbrode SD, Espelie KE, Shelton AM (1991) Behavior of neonate diamondback moth larvae [*Plutella xylostella* (L.)] on leaves and on extracted leaf waxes of resistant and susceptible cabbages. J Chem Ecol 17:1691–1704. https://doi.org/10.1007/BF00984697

Fatouros NE, Paniagua Voirol LR, Drizou F, Doan QT, Pineda A, Frago E, van Loon JJ (2015) Role of large cabbage white butterfly male-derived compounds in elicitation of direct and indirect egg-killing defenses in the black mustard. Front Plant Sci 6:794. https://doi.org/10.3389/fpls.2015.00794

Feng B, Qian K, Du YJ (2017) Floral volatiles from *Vigna unguiculata* are olfactory and gustatory stimulants for oviposition by the bean pod borer moth *Maruca vitrata*. Insects 8:60. https://doi.org/10.3390/insects8020060

Fernández PC, Braccini CL, Dávila C, Barrozo RB, Aráoz MVC, Cerrillo T, Gershenzon J, Reichelt M, Zavala JA (2019) The use of leaf surface contact cues during oviposition explains field preferences in the willow sawfly *Nematusoligospilus*. Sci Rep 9:4946. https://doi.org/10.1038/s41598-019-41318-7

Foster SP, Howard AJ (1998) Influence of stimuli from *Camellia japonica* on ovipositional behavior of generalist herbivore *Epiphyas postvittana*. J Chem Ecol 24:1251–1275. https://doi.org/10.1023/A:1022455120922

Gawariya SC, Chopra NK, Chopra N, Harika AS (2015) Effect of date of sowing and crop geometry on growth and yield parameters of forage mustard (var. Chinese Cabbage). Afr J Agric Res 10:3292–3295. https://doi.org/10.5897/AJAR2015.9745

Golizadeh A, Kamali K, Fathipour Y, Abbasipour H (2009) Life table of the diamondback moth, *Plutella xylostella* (L.) (Lepidoptera: Plutellidae) on five cultivated brassicaceous host plants. J Agric Sci Technol 11:115–124

Grant GG, Zhao B, Langevin D (2000) Oviposition response of spruce budworm (Lepidoptera: Tortricidae) to aliphatic carboxylic acids. Environ Entomol 29:164–170. https://doi.org/10.1093/ee/29.2.164

Griese E, Pineda A, Pashalidou FG, Iradi EP, Hilker M, Dicke M, Fatouros NE (2020) Plant responses to butterfly oviposition

partly explain preference–performance relationships on different brassicaceous species. Oecologia 192:463–475. https://doi.org/10.1007/s00442-019-04590-y

Gripenberg S, Mayhew PJ, Parnell M, Roslin T (2010) A meta-analysis of preference–performance relationships in phytophagous insects. Ecol Lett 13:383–393. https://doi.org/10.1111/j.1461-0248.2009.01433.x

Gupta G, Bhattacharya AK (2008) Assessing toxicity of post-emergence herbicides to the *Spilarctia obliqua* Walker (Lepidoptera: Arctiidae). J Pest Sci 81:9–15. https://doi.org/10.1007/s10340-007-0175-8

Hasan F, Ansari MS (2010) Effect of different cole crops on the biological parameters of *Pieris brassicae* (L.) (Lepidoptera: Pieridae) under laboratory conditions. J Crop Sci Biotechnol 13:195–202. https://doi.org/10.1007/s12892-010-0025-2

Huang B, Shi Z, Hou Y (2014) Host selection behavior and the fecundity of *Plutella xylostella* (Lepidoptera: Plutellidae) on multiple host plants. J Insect Sci 14:251. https://doi.org/10.1093/jisesa/ieu113

Hussain M, Gao J, Bano S, Wang L, Lin Y, Arthurs S, Qasim M, Mao R (2020) Diamondback moth larvae trigger host plant volatiles that lure its adult females for oviposition. Insects 11:725. https://doi.org/10.3390/insects11110725

Ikeura H, Kobayashi F, Hayata Y (2010) How do *Pieris rapae* search for Brassicaceae host plants? Biochem System Ecol 38:1199–1203. https://doi.org/10.1016/j.bse.2010.12.007

Jetter R, Schäffer S (2001) Chemical composition of the *Prunus laurocerasus* leaf surface. Dynamic changes of the epicuticular wax film during leaf development. Plant Physiol 126:1725–1737. https://doi.org/10.1104/pp.126.4.1725

Jetter R, Schäffer S, Riederer M (2000) Leaf cuticular waxes are arranged in chemically and mechanically distinct layers: evidence from *Prunus laurocerasus* L. Plant Cell Environ 23:619–628. https://doi.org/10.1046/j.1365-3040.2000.00581.x

Jetter R, Kunst L, Samuels AL (2006) Composition of plant cuticular waxes. In: Riederer M, Müller C (eds) Biology of the plant cuticle. Blackwell Publishing, Oxford, pp 145–175

Karmakar A, Malik U, Barik A (2016) Effects of leaf epicuticular wax compounds from *Solena amplexicaulis* (Lam.) Gandhi on olfactory responses of a generalist insect herbivore. Allelopath J 37:253–272

Karmakar P, Pal S, Chakraborty G (2022) Effects of cabbage cultivars on the food consumption and utilization parameters of diamondback moth, *Plutella xylostella* (L.). Int J Trop Insect Sci 42:83–92. https://doi.org/10.1007/s42690-021-00520-9

Koza A, Sahu AK, Das S, Patra NK (2018) Economics of cabbage cultivation and post-harvest losses in Phek district of Nagaland. Econ Aff 63:229–235. https://doi.org/10.30954/0424-2513.2018.00150.28

Kumar H (2004) Orientation, feeding, and ovipositional behavior of diamondback moth, *Plutella xylostella* (Lepidoptera: Plutellidae), on transgenic cabbage expressing Cry1Ab toxin of *Bacillus thuringiensis* (Berliner). Environ Entomol 33:1025–1031. https://doi.org/10.1603/0046-225X-33.4.1025

Kumar R, Ali S (2010) Efficacy of botanical pesticides against *Spilarctia obliqua* in *Sesamum indicum*. Ann Plant Prot Sci 18:223–224

Kumar V, Kaur S, Kumar J, Gupta Y (2018) Development of white butterfly, *Pieris brassicae* L. in cabbage ecosystem. J Entomol Zool Stud 6:1270–1273

Kumar P, Brar JS, Singh G (2020) Life cycle of cabbage caterpillar, *Pieris brassicae* Linn. (Lepidoptera: Pieridae) on cabbage leaves in Talwandi Sabo (Punjab). J Entomol Zool Stud 8:766–769

Li G, Ishikawa Y (2006) Leaf epicuticular wax chemicals of the Japanese knotweed *Fallopia japonica* as oviposition stimulants for *Ostrinia latipennis*. J Chem Ecol 32:595–604. https://doi.org/10.1007/s10886-005-9022-7

Li F, Li K, Wu LJ, Fan YL, Liu TX (2020) Role of biogenic amines in oviposition by the diamondback moth *Plutella Xylostella* L. Front Physiol 11:475. https://doi.org/10.3389/fphys.2020.00475

Little CM, Chapman TW, Hillier NK (2019) Considerations for insect learning in integrated pest management. J Insect Sci 19:1–14. https://doi.org/10.1093/jisesa/iez064

Lucas-Barbosa D, Sun P, Hakman A, van Beek TA, van Loon JJA, Dicke M (2016) Visual and odour cues: plant responses to pollination and Herbivory affect the behaviour of flower visitors. Funct Ecol 30:431–441. https://doi.org/10.1111/1365-2435.12509

Malik U, Mitra S, Barik A (2017) Attraction of the biocontrol agent, *Galerucella placida* Baly (Coleoptera: Chrysomelidae) to the leaf surface alkanes of the weed, *Polygonum orientale* L. Allelopath J 40:103–116. https://doi.org/10.26651/2017-40-1070

Mitra S, Sarkar N, Barik A (2017) Long-chain alkanes and fatty acids from *Ludwigia octovalvis* weed leaf surface waxes as shortrange attractant and ovipositional stimulant to *Altica cyanea* (Weber) (Coleoptera: Chrysomelidae). Bull Entomol Res 107:391–400. https://doi.org/10.1017/s0007485316001012

Mitra P, Mobarak SH, Debnath R, Barik A (2019) The role of *Lathyrus sativus* flower surface wax in short-range attraction and stimulant for nymph laying by an adult viviparous aphid. Bull Entomol Res 110:231–241. https://doi.org/10.1017/S0007485319000531

Mitra P, Das S, Barik A (2020) Leaf waxes from *Lathyrus sativus*: short-range attractant and stimulant for nymph laying in a viviparous insect. Chemoecology 30:117–129. https://doi.org/10.1007/s00049-020-00303-7

Mobarak SH, Koner A, Mitra S, Mitra P, Barik A (2020) The importance of leaf surface wax as short-range attractant and oviposition stimulant in a generalist Lepidoptera. J Appl Entomol 144:616–631. https://doi.org/10.1111/jen.12769

Mukherjee A, Sarkar N, Barik A (2014) Long-chain free fatty acids from *Momordica cochinchinensis* leaves as attractants to its insect pest, *Aulacophora foveicollis* Lucas (Coleoptera: Chrysomelidae). J Asia-Pac Entomol 17:229–234. https://doi.org/10.1016/j.aspen.2014.01.010

Mukherjee A, Sarkar N, Barik A (2015) Leaf surface n–alkanes of *Momordica cochinchinensis* Spreng as short–range attractants for its insect pest, *Aulacophora foveicollis* Lucas (Coleoptera: Chrysomelidae). Alleop J 36:109–122

Müller C, Hilker M (2001) Host finding and oviposition behavior in a chrysomelid specialist–the importance of host plant surface waxes. J Chem Ecol 27:985–994. https://doi.org/10.1023/a:1010343205114

Müller C, Riederer M (2005) Plant surface properties in chemical ecology. J Chem Ecol 31:2621–2651. https://doi.org/10.1007/s10886-005-7617-7

Neik TX, Barbetti MJ, Batley J (2017) Current status and challenges in identifying disease resistance genes in *Brassica napus*. Front Plant Sci 8:1788. https://doi.org/10.3389/fpls.2017.01788

Obermeier C, Mason AS, Meiners T, Petschenka G, Rostás M, Will T, Wittkop B, Austel N (2022) Perspectives for integrated insect pest protection in oilseed rape breeding. Theor Appl Genet. https://doi.org/10.1007/s00122-022-04074-3

Parr MJ, Tran BMD, Simmonds MSJ, Kite GC, Credland PF (1998) Influence of some fatty acids on oviposition by the bruchid beetle, *Callosobruchus maculatus*. J Chem Ecol 24:1577–1593

Passos DA, Silva-Torres CSA, Siqueira HAA (2020) Behavioral response and adaptive cost in resistant and susceptible *Plutella xylostella* to Chlorantraniliprole. Bull Entomol Res 110:96–105. https://doi.org/10.1017/S0007485319000300

Phelan PL, Roelofs CJ, Youngman RR, Baker TC (1991) Characterization of chemicals mediating ovipositional host-plant finding by *Amyelois transitella* females. J Chem Ecol 17:599–613. https://doi.org/10.1007/BF00982129

Pivnick KA, Jarvis BJ, Slater GP, Gillott C, Underhill EW (1990) Attraction of the diamondback moth (Lepidoptera: Plutellidae) to volatiles of Oriental mustard: the influence of age, sex, and prior exposure to mates and host plants. Environ Entomol 19:704–709. https://doi.org/10.1093/ee/19.3.704

Pivnick KA, Jarvis BJ, Slater GP (1994) Identification of olfactory cues used in host-plant finding by diamondback moth, *Plutella xylostella* (Lepidoptera: Plutellidae). J Chem Ecol 20:1407–1427. https://doi.org/10.1007/BF02059870

Reddy GV, Guerrero A (2000) Behavioral responses of the diamondback moth, *Plutella xylostella*, to green leaf volatiles of *Brassica oleracea* Subsp. capitata. J Agric Food Chem 48:6025–6029. https://doi.org/10.1021/jf0008689

Reddy GVP, Tabone E, Smith MT (2004) Mediation of host selection and oviposition behavior in the diamondback moth *Plutella xylostella* and its predator *Chrysoperla carnea* by chemical cues from cole crops. Biol Control 29:270–277. https://doi.org/10.1016/S1049-9644(03)00162-2

Renwick J, Chew FS (1994) Oviposition behavior in Lepidoptera. Annu Rev Entomol 39:377–400. https://doi.org/10.1146/annurev.en.39.010194.002113

Roy N (2019a) Jute leaf physicochemical cues mediated behavioral responses of *Diacrisia casignetum* Kollar. Agric Res 8:287–296. https://doi.org/10.1007/s40003-018-0362-2

Roy N (2019b) Life table and economic threshold concept for ecologically sustainable management of *Diacrisia casignetum* Kollar (Lepidoptera: Arctiidae) on jute. Entomon 44:103–110. https://doi.org/10.33307/entomon.v44i.436

Roy N (2020) Population ecology and ETs based time series for climate smart pest management of *Spilosoma obliqua* Walker. Entomon 45:15–30. https://doi.org/10.33307/entomon.v45i1.500

Roy N (2021a) Population dynamics and economic thresholds-based time series for smart pest management of sesame. Int J Trop Insect Sci. https://doi.org/10.1007/s42690-021-00437-3

Roy N (2021b) Synergism in host selection behaviour of three generalists towards leaf cuticular wax of sesame cultivars. Neotrop Entomol 50:812–827. https://doi.org/10.1007/s13744-021-00892-0

Roy N, Barik A (2012) Alkanes used for host recognition by the arctiid moth, *Diacrisia casignetum* Kollar. J Entomol Res 36:345–350

Roy N, Barik A (2014) Long-chain fatty acids: semiochemicals for host location by the insect pest, *Diacrisia casignetum*. J Kansas Entomol Soc 87:22–36. https://doi.org/10.2317/JKES130521.1

Roy N, Laskar S, Barik A (2012a) The attractiveness of odorous esterified fatty acids to the potential biocontrol agent, *Altica cyanea*. J Asia Pac Entomol 15:277–282. https://doi.org/10.1016/j.aspen.2012.03.001

Roy N, Laskar S, Barik A (2012b) Determination of *n*-alkane profile through developmental state of sunflower leaves. S Pac J Nat Appl Sci 30:72–76. https://doi.org/10.1071/sp12008

Salim HA, Abed MS (2015) Effect of botanical extracts, biological and chemical control against *Spilosoma obliqua* on cabbage (*Brassica oleracea*). J Entomol Zool Stud 3:43–46

Sarfraz M, Keddie BA (2005) Conserving the efficacy of insecticides against *Plutella xylostella* (L.) (Lep., Plutellidae). J Appl Entomol 129:149–157. https://doi.org/10.1111/j.1439-0418.2005.00930.x

Sarfraz M, Dosdall LM, Keddie BA (2007) Resistance of some cultivated Brassicaceae to infestations by *Plutella xylostella* (Lepidoptera: Plutellidae). J Econ Entomol 100:215–224. https://doi.org/10.1603/0022-0493(2007)100[215:roscbt]2.0.co;2

Schäpers A, Carlsson MA, Gamberale-Stille G, Janz N (2015) The Role of olfactory cues for the search behavior of a specialist and generalist butterfly. J Insect Behav 28:77–87. https://doi.org/10.1007/s10905-014-9482-0

Schoonhoven LM, van Loon JJA, Dicke M (2005) Insect-plant biology. Oxford University Press, Oxford

Shakeel M, Farooq M, Nasim W, Akram W, Khan FZA, Jaleel W, Zhu X, Yin H, Li S, Fahad S, Hussain S, Chauhan BS, Jin F (2017) Environment polluting conventional chemical control compared to an environmentally friendly IPM approach for control of diamondback moth, *Plutella xylostella* (L.), in China: a review. Environ Sci Pollut Res Int 24:14537–14550. https://doi.org/10.1007/s11356-017-8996-3

Singh RK, Singh Y, Singh AK, Kumar R, Singh VK (2010) Productivity and economics of mustard (*Brassica juncea*) varieties as influenced by different fertility levels under late sown condition. Ind J Soil Conserv 38:121–124

Singh R, Koul O, Rup PJ, Jindal J (2011) Oviposition and feeding behavior of the maize borer, *Chilo partellus*, in response to eight essential oil allelochemicals. Entomol Exp Appl 138:55–64. https://doi.org/10.1111/j.1570-7458.2010.01071.x

Song C, Ma L, Zhao J, Xue Z, Yan X, Hao C (2022) Electrophysiological and behavioral responses of *Plutella xylostella* (Lepidoptera: Plutellidae) to volatiles from a non-host plant, geranium, *Pelargonium hortorum* (Geraniaceae). J Agric Food Chem 70:5982–5992. https://doi.org/10.1021/acs.jafc.1c08165

Spencer JL, Pillai S, Bernays EA (1999) Synergism in the oviposition behavior of *Plutella xylostella*: sinigrin and wax compounds. J Insect Behav 12:483–500. https://doi.org/10.1023/A:1020914723562

Tandayu E, Borpatragohain P, Mauleon R, Kretzschmar T (2022) Genome-wide association reveals trait loci for seed glucosinolate accumulation in Indian mustard (*Brassica juncea* L.). Plants (basel) 11:364. https://doi.org/10.3390/plants11030364

Tripathi RS (1999) Economics of cabbage production in high-hills of Uttar Pradesh. Ind J Hort 56:343–347

Udayagiri S, Mason CE (1997) Epicuticular wax chemicals in *Zea mays* influences oviposition in *Ostrinia nubilalis*. J Chem Ecol 23:1675–1687. https://doi.org/10.1023/B:JOEC.0000006443.72203.f7

Van Loon JJA, Blaakmeer A, Griepink FC, Van Beek TA, Schoonhoven LM, De Groot Æ (1992) Leaf surface compound from *Brassica oleracea* (Cruciferae) induces oviposition by *Pieris brassicae* (Lepidoptera: Pieridae). Chemoecology 3:39–44. https://doi.org/10.1007/BF01261455

Vuorinen T, Nerg AM, Ibrahim MA, Reddy GV, Holopainen JK (2004) Emission of *Plutella xylostella*-induced compounds from cabbages grown at elevated CO_2 and orientation behavior of the natural enemies. Plant Physiol 135:1984–1992. https://doi.org/10.1104/pp.104.047084

Wang Y, Wang J, Chai G, Li C, Hu Y, Chen X, Wang Z (2015) Developmental changes in composition and morphology of cuticular waxes on leaves and spikes of glossy and glaucous Wheat (*Triticum aestivum* L.). PLoS ONE 10:e0141239. https://doi.org/10.1371/journal.pone.0141239

Warad M, Kalleshwaraswamy CM (2017) Biology of Bihar hairy caterpillar, *Spilarctia obliqua* (Walker) (Erebidae: Lepidoptera) on field bean. Agric Update 12:1256–1260. https://doi.org/10.15740/HAS/AU/12.TECHSEAR(5)2017/1256-1260

Wee SK (2016) Effects of conspecific herbivory and mating status on host searching and oviposition behavior of *Plutella xylostella* (Lepidoptera: Plutellidae) in relation to its host, *Brassica oleracea* (Brassicales: Brassicaceae). Florida Entomol 99:159–165. https://doi.org/10.1653/024.099.sp119

Zar JH (1999) Biostatistical analysis. Prentice Hall, Upper Saddle River, NJ, p 663

Zhu JY, Xiang ZW, Zhang SZ, Wu LN, Liu TX (2021) Adaptations of *Plutella xylostella* adult females and larvae to waxy

host plants. J Pest Sci 95:203–214. https://doi.org/10.1007/s10340-021-01366-3