

# 实蝇觅食、交配和产卵行为相关的 信息化合物研究及其应用进展\*

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**摘 要** 实蝇是危害果实和蔬菜等园艺作物的一类具有毁灭性和检疫性的重要害虫, 分布地区广、繁殖快, 对果蔬产业造成了严重的经济损失。实蝇成虫产卵于寄主植物组织内, 幼虫在组织内潜食, 防治困难。信息化合物, 包括虫源信息化合物、植物源信息化合物和其它来源的信息化合物, 因具有活性高、专一性强等特点成为实蝇害虫绿色防控的首选策略。因此, 本文系统综述了与实蝇成虫觅食、交配和产卵行为相关的虫源信息化合物、植物源信息化合物和其它来源信息化合物的研究进展及其在害虫防治中的应用现状, 为实蝇害虫综合治理提供理论基础和指导。

**关键词** 实蝇; 性信息素; 植物挥发物; 信息化合物; 绿色防控

## Progress in research on the application of semiochemicals related to the foraging, mating and oviposition behavior of the fruit fly

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**Abstract** Fruit flies are destructive quarantine pests that harm horticultural crops. Their wide distribution and high fecundity cause large economic losses to the fruit and vegetable industry. Moreover, adult females lay their eggs within host plant tissue where the larvae feed making them difficult to control. Semiochemicals, including those derived from insects, plants, and other sources, due to their high activity and strong specificity, have become the preferred tools for the environmentally- friendly prevention and control of fruit flies. Therefore this review focuses on semiochemicals related to foraging, mating, and oviposition behavior and the application of these in pest control, and then provides guidance and a theoretical basis for the integrated management of Tephritidae fruit flies.

**Key words** fruit fly; sex pheromones; plant volatiles; semiochemicals; green prevention and control

实蝇 (Tephritidae fruit fly) 隶属双翅目 (Diptera) 实蝇科 (Tephritidae), 包含近 500 属约 5 000 种, 是双翅目昆虫中最大的科之一, 广泛分布于世界各地, 而亚热带、温带及热带是其分布主要区域 (李志红等, 2013; 高媛惠等, 2016; Qin *et al.*, 2018)。实蝇科中的按实蝇属

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(*Anastrepha*)、果实蝇属(*Bactrocera*)、腊实蝇属(*Ceratitis*)、绕实蝇属(*Rhagoletis*)和簇果实蝇属(*Zeugodacus*)，其成虫在果实或蔬菜的果实组织内产卵，幼虫在果肉内部钻蛀取食危害，成为果蔬产业上的一类重要害虫(张宏宇和李红叶, 2018)。

园艺作物在世界农业生产板块中占据重要份额(Ravichandra, 2014)，大量产品因果实中隐藏的幼虫或卵导致果品不符合进出口检疫条例而严重影响其经济效益(Kibira *et al.*, 2015)，如橘小实蝇*B. dorsalis*危害的果实每年对非洲造成的损失近20亿美元(Dohino *et al.*, 2017)。此外，实蝇成虫繁殖速度快，能随受害果蔬或其它媒介如包装袋等广泛传播扩散，极易形成爆发性危害，对果蔬的现代化产业健康发展造成危险性的冲击(王在凌等, 2020)。因此，世界各地对实蝇严加防控，采取有力措施控制、遏制乃至根除该类害虫种群(Papadopoulos, 2014)。

对实蝇的防治主要是以诱杀为主，农业和化学防治为辅的综合治理(IPM)(张宏宇和李红叶, 2018)。随着绿色发展理念逐步兴起，实蝇绿色防控技术迅速发展(Navarro-Llopis *et al.*, 2011)，采用诱剂诱杀成为绿色防控技术的重要措施。常用诱剂主要为信息化合物诱剂(性信息素诱剂和类信息素诱剂)和食饵类诱剂。性信息素诱剂是以实蝇性信息素或其结构类似物为活性成分开发的具有引诱能力的诱剂(Witzgall *et al.*, 2010; Cui and Zhu, 2016)，如实蝇在性成熟期释放的挥发性化学物质(Shelly *et al.*, 2014; 李运娜, 2018)。类信息素是来自于某些寄主植物的挥发物或代谢物等能引起昆虫趋向反应的物质(林嘉等, 2021)，如羽化后成虫因觅食补充营养、雌性寻找产卵寄主等生理特性会趋向于选择酵母或植物的挥发化合物(El-Ghany, 2019)。信息化合物具有活性高、专一性强且不会对非靶标生物造成负面影响等特点，相关技术备受重视，应用前景广阔(王留洋等, 2022)。

本综述中，通过对国内外现有的相关文献分

析，重点阐述了与实蝇觅食、交配和产卵行为相关的虫源信息化合物、植物源信息化合物和其它来源信息化合物的来源、生物活性行为测定方法、研究现状及其在害虫防治中的应用价值，为实蝇害虫综合治理提供理论基础及技术参考。

## 1 实蝇虫源信息化合物

昆虫信息化合物参与种内和种间的交流，影响其行为和生理反应(Tinsworth, 1990; Rodriguez and Niemeyer, 2005; Brezolin *et al.*, 2018)。来自昆虫虫体挥发物中的信息化合物，根据功能的不同，将其分为性信息素、寄主标记信息素、聚集信息素及利它素等信息素(Butenandt *et al.*, 1959; Guo *et al.*, 2020; Scolari *et al.*, 2021)。其中，性信息素对性成熟的成虫发挥着求偶和交配的生理作用；寄主标记信息素是指昆虫在寄主上产卵后，通过释放某种化学物质影响同种的排卵行为，从而减少在已经利用的资源上花费的时间和有限宿主资源的竞争(Nufio and Papaj, 2001)。可见，信息化合物在昆虫成虫期发挥着至关重要的作用，如寻求食物、配偶和寄主定位等(Keeling *et al.*, 2004)。

实蝇性信息素主要来源于虫体和直肠腺，寄主标记信息素主要来自于虫体排泄物(表1)。南美实蝇*A. fraterculus*雄虫虫体挥发物中的 $\alpha$ -蒎烯、柠檬烯、(Z)-3-壬烯-1-醇、(E,Z)-3,6-壬二烯-1-醇、 $\alpha$ -法尼烯和(S,S)-(-)-epianastrephin 6种主要物质可以触发雌虫的电生理反应，且在田间试验中证实对其雌虫有显著引诱效果(Milet-Pinheiro *et al.*, 2015)。柑橘大实蝇*B. minax*雌虫虫体挥发物(R)-(+)-柠檬烯对其雄虫具有强烈引诱力(张宏宇, 2015; 李运娜, 2018)。此外，许多研究者对实蝇直肠腺挥发物分离后发现其对实蝇成虫有引诱行为反应(Haniotakis *et al.*, 1977; Mazomenos and Haniotakis, 1981; Carpita *et al.*, 2012; Canale *et al.*, 2015; Noushini *et al.*, 2019)。杨桃实蝇*B. carambolae*雄虫直肠腺挥发物6-氧代-1-壬醇和N-3-甲基丁基乙酰胺

表 1 实蝇虫源信息化化合物  
Table 1 Semiochemicals of Tephritidae from male/female borne

| 实蝇属<br>Genera             | 实蝇种<br>Species                | 信息素成分<br>Compounds                                                                                                                                                                | 物质来源<br>Sources                         | 行为<br>效应 <sup>a</sup><br>Behaviour | 活性测定实验 <sup>b</sup><br>Behavioural experiments |                                                                 |                            | 参考文献<br>References                   |
|---------------------------|-------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------|------------------------------------|------------------------------------------------|-----------------------------------------------------------------|----------------------------|--------------------------------------|
|                           |                               |                                                                                                                                                                                   |                                         |                                    | EAG or<br>GC-EAD                               | Y 型嗅觉实验或<br>室内网笼实验<br>Y-tube or<br>Laboratory<br>cage bioassays | 田间试验<br>Field<br>bioassays |                                      |
| 按实蝇属<br><i>Anastrepha</i> | 南美实蝇<br><i>A. fraterculus</i> | $\alpha$ -蒎烯 $\alpha$ -Pinene; 柠檬烯 Limonene; (Z)-3-壬烯-1-醇 (Z)-3-nonen-1-ol; (E,Z)-3,6-壬二烯-1-醇(E,Z)-3,6-nonadien-1-ol; $\alpha$ -法尼烯 $\alpha$ -Farnesene; (S,S)-(-)-epianastrephin | 雄虫虫体<br>Male-borne                      | ♀                                  | +                                              | +                                                               | +                          | Milet-Pinheiro <i>et al.</i> , 2015  |
|                           | 墨西哥实蝇<br><i>A. ludens</i>     | (Z)-3-壬烯醇 (Z)-3-nonenol; (Z,Z)-3,6-壬二烯醇 (Z,Z)-3,6-nonadienol; (S,S)-(-)-epianastrephin                                                                                            | 雄虫虫体<br>Male-borne                      | ♀                                  |                                                | +                                                               |                            | Robacker and Hart, 1985              |
|                           |                               | 2-(2,14-二甲基十五烷酰氨基)戊二酸<br>2-(2,14-Dimethylpentadecanoylamino) pentane-dioic acid                                                                                                   | 雌虫排泄物<br>Faeces from Female             | ♀                                  |                                                | +                                                               |                            | Aluja-Schuneman <i>et al.</i> , 2001 |
|                           | 西印度实蝇<br><i>A. obliqua</i>    | (Z)-3-壬烯醇 (Z)-3-nonenol; $\beta$ -法尼烯 $\beta$ -Farnesene                                                                                                                          | 雄虫虫体<br>Male-borne                      | ♀♂                                 |                                                | +                                                               |                            | López-Guillén <i>et al.</i> , 2011   |
| 果实蝇属<br><i>Bactrocera</i> | 暗色实蝇<br><i>A. serpentina</i>  | 2,5-二甲基吡嗪 2,5-dimethylpyrazine (DMP); 三甲基吡嗪 Trimethylpyrazine (TMP); 3,6-二氢-2,5-二甲基吡嗪 3,6-dihydro-2,5-dimeth-ylpyrazine (DHDMP)                                                   | 雄虫虫体<br>Male-borne                      | ♀                                  | +                                              |                                                                 |                            | Robacker <i>et al.</i> , 2009        |
|                           | 加勒比实蝇<br><i>A. suspensa</i>   | Z-3-壬烯-1-醇 Z-3-nonen-1-ol; Z,Z-3,6-壬二烯-1-醇 Z,Z-3,6-nonadien-1-ol                                                                                                                  | 雄虫虫体<br>Male-borne                      | ♀                                  |                                                | +                                                               |                            | Nation, 1983                         |
|                           | 杨桃实蝇<br><i>B. carambolae</i>  | 6-氧代-1-壬醇 6-oxo-1-nonanol; N-3-甲基丁基乙酰胺 N-3-methylbutyl acetamide                                                                                                                  | 雄虫直肠腺<br>Male rectal gland              | ♀                                  |                                                | +                                                               |                            | Wee and Tan, 2005                    |
|                           | 香蕉实蝇<br><i>B. musae</i>       | 月桂酸乙酯 Ethyl laurate; 丁酸乙酯 Ethyl butanoate; (E,E)-2,8-二甲基-1,7-二氧杂螺[5.5]十一烷 (E,E)-2,8-dimethyl-1,7-dioxaspiro[5.5]undecane                                                          | 雄、雌虫<br>直肠腺<br>Male/Female rectal gland | ♀♂                                 | +                                              |                                                                 |                            | Noushini <i>et al.</i> , 2019        |
|                           | 橄榄实蝇<br><i>B. oleae</i>       | (Z)-9-二十三烯 (Z)-9-tricosene                                                                                                                                                        | 雄虫直肠腺<br>Male rectal gland              | ♀                                  |                                                | +                                                               |                            | Carpita <i>et al.</i> , 2012         |

续表 1 (Table 1 continued)

| 实蝇属<br>Genara               | 实蝇种<br>Species          | 信息素成分<br>Compounds                                                                                                                                                                                                                                                                                            | 物质来源<br>Sources                            | 行为<br>效应 <sup>a</sup><br>Behaviour | 活性测定实验 <sup>b</sup><br>Behavioural experiments |                                                                 |                            | 参考文献<br>References                                                       |
|-----------------------------|-------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------|------------------------------------|------------------------------------------------|-----------------------------------------------------------------|----------------------------|--------------------------------------------------------------------------|
|                             |                         |                                                                                                                                                                                                                                                                                                               |                                            |                                    | EAG or<br>GC-EAD                               | Y 型嗅觉实验或<br>室内网笼实验<br>Y-tube or<br>Laboratory<br>cage bioassays | 田间试验<br>Field<br>bioassays |                                                                          |
| 果实蝇属<br><i>Bactrocera</i>   | 橄榄实蝇<br><i>B. oleae</i> | 1,7-二氧杂螺 (5.5) 十一烷<br>undecane                                                                                                                                                                                                                                                                                | 雌虫直肠腺<br>Female rectal<br>gland            | ♂                                  |                                                | +                                                               | +                          | Haniotakis <i>et al.</i> ,<br>1977;<br>Mazomenos and<br>Haniotakis, 1981 |
|                             |                         | 癸酸乙酯 Ethyl decanoate;<br>十六烷酸甲酯 Methyl hexadecanoate                                                                                                                                                                                                                                                          | 雄、雌虫<br>直肠腺<br>Male/Female<br>rectal gland | ♀♂                                 | +                                              | +                                                               |                            | Canale <i>et al.</i> ,<br>2015                                           |
|                             |                         | E-6-壬烯-1-醇 E-6-nonen-1-ol; 对异丙基甲苯<br><i>p</i> -Cymene                                                                                                                                                                                                                                                         | 雌虫虫体<br>Female-<br>borne                   | ♀                                  |                                                | +                                                               | +                          | Gariboldi <i>et al.</i> ,<br>1982                                        |
| 桃实蝇<br><i>B. zonata</i>     |                         | 2-乙基-3,5,6-三甲基吡嗪 2-Ethyl-3,5,6-trimethylpyrazine; (E,E)-2,8-二甲基-1,7-二氧杂螺 [5.5] 十一烷 (E,E)-2,8-dimethyl-1,7-dioxaspiro[5.5]undecane; 十二烷酸乙酯 Ethyl dodecanoate                                                                                                                                                   | 雄、雌虫<br>虫体 Male/<br>Female-borne           | ♀♂                                 | +                                              |                                                                 |                            | Levi-Zada <i>et al.</i> ,<br>2020                                        |
|                             |                         | $\beta$ -石竹烯 $\beta$ -caryophyllene                                                                                                                                                                                                                                                                           | 雌虫直肠腺<br>Male-rectal<br>gland              | ♂                                  |                                                |                                                                 | +                          | Tokushima <i>et al.</i> ,<br>2010; Wee <i>et al.</i> ,<br>2018           |
| 番石榴实蝇<br><i>B. correcta</i> |                         | 十二烷酸乙酯 Ethyl dodecanoate; 十四烷酸乙酯 Ethyl tetradecanoate; (E)-9-十六碳烯酸乙酯 Ethyl (E)-9-hexadecenoate; 十六烷酸乙酯 Ethyl hexadecanoate; (Z)-9-十八碳烯酸乙酯 Ethyl (Z)-9-octadecenoate; 辛醛 Octanal; N-(3-甲基丁基)乙酰胺 N-(3-methylbutyl) acetamide; (Z)-9-二十三烯 (Z)-9-tricosene; 十八碳烯酸乙酯 Ethyl octadecenoate; 二十烷酸乙酯 Ethyl eicosanoate | 雌虫直肠腺<br>Female-rectal<br>gland            | ♀♂                                 |                                                | +                                                               |                            | Zhang <i>et al.</i> ,<br>2019                                            |
|                             |                         | 2-烯丙基-4,5-二甲氧基苯酚 2-allyl-4,5-dimethoxyphenol; 松柏醇 Coniferyl alcohol                                                                                                                                                                                                                                           | 雄虫虫体<br>Male-borne                         | ♂                                  |                                                |                                                                 | +                          | Nishida <i>et al.</i> ,<br>1988                                          |

续表 1 (Table 1 continued)

| 实蝇属<br>Genera             | 实蝇种<br>Species              | 信息素成分<br>Compounds                                                                                                                                                                                                                       | 物质来源<br>Sources             | 行为<br>效应 <sup>a</sup><br>Behaviour | 活性测定实验 <sup>b</sup><br>Behavioural experiments |                                                                 |                            | 参考文献<br>References               |
|---------------------------|-----------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------|------------------------------------|------------------------------------------------|-----------------------------------------------------------------|----------------------------|----------------------------------|
|                           |                             |                                                                                                                                                                                                                                          |                             |                                    | EAG or<br>GC-EAD                               | Y 型嗅觉实验或<br>室内网笼实验<br>Y-tube or<br>Laboratory<br>cage bioassays | 田间试验<br>Field<br>bioassays |                                  |
| 果实蝇属<br><i>Bactrocera</i> | 柑橘大实蝇<br><i>B. minax</i>    | (R)-(+)-柠檬烯 (R)-(+)-Limonene                                                                                                                                                                                                             | 雌虫虫体<br>Female-borne        | ♂                                  |                                                |                                                                 | +                          | 张宏宇, 2015;<br>李运娜, 2018          |
|                           |                             | N-(3-甲基丁基)乙酰胺 N-(3-methyl-butyl) acetamide                                                                                                                                                                                               | 雌虫虫体<br>Female-borne        | ♀♂                                 | +                                              |                                                                 |                            | 李明杰等, 2021                       |
| 腊实蝇属<br><i>Ceratitis</i>  | 地中海实蝇<br><i>C. capitata</i> | (E) 6-壬烯酸甲酯 Methyl (E)-6-nonenolate; Ejl-6-nonen-l-ol                                                                                                                                                                                    | 雄虫虫体<br>Male-borne          | ♀                                  |                                                | +                                                               | +                          | Jacobson <i>et al.</i> , 1973    |
|                           |                             | 谷氨酸 Glutamic acid                                                                                                                                                                                                                        | 雌虫排泄物<br>Faeces from female | ♀                                  |                                                | +                                                               |                            | Cheseto <i>et al.</i> , 2018     |
|                           | 纳塔尔实蝇<br><i>C. rosa</i>     | 谷胱甘肽 Glutathione                                                                                                                                                                                                                         | 雌虫排泄物<br>Faeces from Female | ♀                                  |                                                | +                                                               |                            | Cheseto <i>et al.</i> , 2017     |
|                           |                             | (-)-δ-庚内酯 (-)-δ-heptalactone                                                                                                                                                                                                             | 雄虫虫体<br>Male-borne          | ♀♂                                 | +                                              |                                                                 | +                          | Bűda <i>et al.</i> , 2020        |
| 绕实蝇属<br><i>Rhagoletis</i> | 沙棘绕实蝇<br><i>R. batava</i>   | 十八烷酸 Octadecanoic; 十九烷酸 Nonadecanoic; 5,8,11,14,17-二十碳五烯酸 5,8,11,14,17-Eicosapentaenoic acid; 5,8,11,14-二十碳五烯酸 5,8,11,14-Eicosatetraenoic acid; 二十烷酸 Eicosanoic acid; 二十二碳六烯酸 4,7,10,13,16,19-Docosahexenoic acid; 二十二烷酸 Docosanoic acid | 雄虫虫体<br>Male-borne          | ♀                                  | +                                              |                                                                 |                            | Raptopoulos <i>et al.</i> , 1995 |
|                           |                             | N-[15 (β-吡喃葡萄糖基)-氧-8-羟基棕榈酰]牛磺酸 N-[15 (β-Glucopyranosyl)-oxy-8-hydroxypalmitoyl] taurine                                                                                                                                                  | 雌虫排泄物<br>Faeces from Female | ♀                                  |                                                | +                                                               | +                          | Hurter <i>et al.</i> , 1987      |
|                           | 欧洲樱桃实蝇<br><i>R. cerasi</i>  |                                                                                                                                                                                                                                          | 雄虫虫体<br>Male-borne          | ♀                                  | +                                              |                                                                 |                            |                                  |

<sup>a</sup> 表示信息化合物对实蝇的活性反应, 其中 ♂ 代表物质对雄性有引诱活性反应; ♀ 代表物质对雌性有引诱活性反应; ♀♂ 代表物质对雌、雄两性均有活性反应。  
<sup>b</sup> 表示信息化合物对实蝇的活性行为反应的测定方式, 其中 + 代表采取此类测定方式。表 2、表 3 同。

<sup>a</sup> represents the response of semiochemicals to Tetrithitidae spp., and ♂ represents the attractant active reaction to males; ♀ represents the attractant active reaction to females. ♀♂ represents the attractant active reaction to both sexes. <sup>b</sup> represents the determination method of semiochemicals' active behavioral response to Tetrithitidae spp., and + represents the adoption of such determination method. The same as table 2 and table 3.

对杨桃实蝇 *B. carambolae* 雌虫有显著引诱效果 (Wee and Tan, 2005)。橄榄实蝇 *B. olea* 雌虫直肠腺挥发物中的 1,7-二氧杂螺(5.5)十一烷对雄虫有显著引诱效果 (Haniotakis *et al.*, 1977; Mazomenos and Haniotakis, 1981)。可见, 实蝇虫体挥发物是发掘潜在性信息素的重要来源。此外, 实蝇不仅在交配前释放利于求偶交配的信息素, 交配后的实蝇雌虫还会释放寄主标记信息素利于对寄主植物的占领, 即寄主标记行为 (Simões *et al.*, 1978; Li *et al.*, 2020)。Porter (1928) 最早在苹果实蝇 *R. Pomonella* 的研究中对寄主标记行为进行了描述, 之后 Prokopy (1972) 和 Cirio 和 Italiana (1972) 首次证实了苹果实蝇 *R. pomonella* 和核桃壳实蝇 *R. complete* 存在这种行为。随后许多研究者开始着力于实蝇寄主标记信息素的研究, 并发现果实蝇属 (*Bactrocera*) 中的橘小实蝇 *B. dorsalis*, 按实蝇属 (*Anastrepha*) 中的加勒比实蝇 *A. suspensa*、巴西番石榴实蝇 *A. sororcula* 及南美实蝇 *A. fraterculus* 等, 腊实蝇属 (*Ceratitis*) 中的地中海实蝇 *C. capitata*、非洲芒果实蝇 *C. cosyra* 和纳塔尔实蝇 *C. rosa*, 绕实蝇属 (*Rhagoletis*) 中的欧洲樱桃实蝇 *R. cerasi* 4 种实蝇属中存在寄主标记行为 (Wiesmann, 1937; Katsoyannos, 1975; Prokopy *et al.*, 1976, 1977, 1978, 1982; Simões *et al.*, 1978; Poloni and Silva, 1986; Hurter *et al.*, 1987; Selivon, 1991; Silva, 1991; Papaj *et al.*, 1992; Aluja *et al.*, 1993; Papaj and Aluja, 1993; Aluja-Schuneman *et al.*, 2001; Aluja and Diaz-Fleischer, 2006; Cheseto *et al.*, 2017; Cheseto *et al.*, 2018; Li *et al.*, 2020), 然而真正被鉴定出的寄主标记信息素却较少 (表 1)。墨西哥实蝇 *A. ludens*、非洲芒果实蝇 *C. cosyra*、纳塔尔实蝇 *C. rosa* 和欧洲樱桃实蝇 *R. cerasi* 的寄主标记信息素分别为 2-(2,14-二甲基十五烷酰氨基)戊二酸 (Papaj and Aluja, 1993; Aluja-Schuneman *et al.*, 2001)、谷胱甘肽 (Cheseto *et al.*, 2017)、谷氨酸 (Cheseto *et al.*, 2018) 和 N-[15(β-吡喃葡萄糖基)-氧-8-羟基棕榈酰]牛磺酸 (Wiesmann, 1937; Katsoyannos, 1975; Hurter *et al.*, 1987)。

研究发现实蝇虫体或直肠腺中还产生聚集信息素(姜勇等, 2002; Guo *et al.*, 2020; Sun *et al.*, 2020; Wei *et al.*, 2022), 能够引起同性或两性昆虫产生聚集行为反应 (Noushini *et al.*, 2019; Zhang *et al.*, 2019; Būda *et al.*, 2020)。橄榄实蝇 *B. oleae* 雌虫虫体挥发物 E-6-壬烯-1-醇和对异丙基甲苯, 室、内外活性行为测定表明对其雌虫有显著引诱效果 (Gariboldi *et al.*, 1982); 西印度实蝇 *A. obliqua* 雄虫虫体挥发物中的(Z)-3-壬烯和β-法尼烯对其雌、雄成虫均有显著引诱效果 (López-Guillén *et al.*, 2011); 番石榴实蝇 *B. correcta* 雌虫直肠腺挥发物(十二烷酸乙酯、十四烷酸乙酯、(E)-9-十六碳烯酸乙酯、十六烷酸乙酯、(Z)-9-十八碳烯酸乙酯、辛醛、N-(3-甲基丁基)乙酰胺、(Z)-9-二十三烯、十八碳烯酸乙酯、二十烷酸乙酯) 对其两性成虫均有引诱效果 (Zhang *et al.*, 2019)。

综上所述, 实蝇信息化合物化学多样性高, 包括酯类、醇类、醛类、羧酸类、环氧化物、酮和苯类化合物等。实蝇通过性信息素、聚集信息素等多种信息素作用于个体间通讯交流, 利于其完成交配、产卵及寻找食物等行为和生理反应 (Gut *et al.*, 2004; Rodriguez *et al.*, 2005; Wyatt, 2014; Brezolin *et al.*, 2018; 巩雪芳等, 2018; Serrano *et al.*, 2019; 李明杰等, 2021)。当前虽然大部分实蝇信息化合物在实验室内证实具有显著引诱效果, 但未在田间进一步验证, 无法实际应用于对实蝇的有效防治, 这是实蝇信息化合物源诱剂开发应用中亟需解决的问题 (林嘉等, 2021; 张栩浩, 2022)。

## 2 实蝇植物源信息化合物

实蝇成虫需要补充营养和寻找寄主植物产卵, 尤其是雌虫表现出对寄主植物挥发性成分的强烈反应和高度敏感性 (王琼等, 2014; 张小娇等, 2020)。因此, 寄主植物或其他植物的次生代谢挥发性物是实蝇信息化合物的重要来源 (表 2)。早在 1912 年, 研究者就发现香茅 *Cymbopogon citratus* 中 4-烯丙基-1,2-二甲氧基苯 (甲基丁香酚, ME) 对桃实蝇 *B. zonata*、橘小实蝇 *B. dorsalis*

表 2 植物源实蝇信息化合物  
Table 2 Semiochemicals of Tetrphitidae from plants

| 实蝇属<br>Genera             | 实蝇种<br>Species            | 信息类化合物<br>Compounds                                                                                                                                                             | 物质来源<br>Sources                  | 行为效应 <sup>a</sup><br>Behaviour | 活性测定法 <sup>b</sup><br>Behavioural experiments |                                               |                         | 参考文献<br>References            |
|---------------------------|---------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------|--------------------------------|-----------------------------------------------|-----------------------------------------------|-------------------------|-------------------------------|
|                           |                           |                                                                                                                                                                                 |                                  |                                | EAG or GC-EAD                                 | 室内网笼实验<br>Y-tube or Laboratory cage bioassays | 田间试验<br>Field bioassays |                               |
| 按实蝇属<br><i>Anastrepha</i> | 墨西哥实蝇<br><i>A. ludens</i> | 1,8-桉叶素 1,8-cineole; 己酸乙酯 Ethyl hexanoate;<br>己醇 Hexanol                                                                                                                        | 发酵佛手瓜<br>Fermented chapote fruit | ♀♂                             | +                                             | +                                             | +                       | Robacker <i>et al.</i> , 1990 |
|                           |                           | 辛酸乙酯 Ethyl octanoate; 苯甲酸乙酯 Ethyl benzoate; 4-萜品醇 4-terpineol;<br>(-)- $\alpha$ -立方体苯 (-)- $\alpha$ -cubebene; $\alpha$ -萜品醇 $\alpha$ -terpineol                                | 发酵佛手瓜<br>Fermented chapote fruit | ♀♂                             | +                                             | +                                             | +                       | Robacker <i>et al.</i> , 1992 |
|                           |                           | 丙二醇 Propylene glycol; 乙酸 Acetic acid; 邻氨基苯甲酸甲酯 Methyl anthranilate; 2-甲基丙酸乙酯 Ethyl 2-methylpropionate; 3-甲基丁酸乙酯 Ethyl 3-methylbutyrate; 2-甲基丁基丙酸酯 2-methylbutyl propionate      | 康科德葡萄<br>Concord grape           | ♀♂                             | +                                             |                                               |                         | Robacker <i>et al.</i> , 2011 |
|                           |                           | 丁酸盐 Butyrate; (E)-3-己烯醇 (E)-3-hexenol; (Z)-3-己烯醇 (Z)-3-hexenol; 己醇 Hexanol; 己酸乙酯 Ethyl hexanoate; 乙酸己酯 Hexyl acetate; (Z)-3-己烯基丁酸酯 (Z)-3-hexenyl butyrate; 辛酸乙酯 Ethyl octanoate | 番石榴 Guava                        | ♀♂                             | +                                             |                                               |                         | Malo <i>et al.</i> , 2005     |

续表 2 (Table 2 continued)

| 实蝇属<br>Genera             | 实蝇种<br>Species             | 信息类化合物<br>Compounds                                                                                                                                                                                                         | 物质来源<br>Sources                             | 行为效应 <sup>a</sup><br>Behaviour | 活性测定法 <sup>b</sup><br>Behavioural experiments |                                               |                            | 参考文献<br>References                      |
|---------------------------|----------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------|--------------------------------|-----------------------------------------------|-----------------------------------------------|----------------------------|-----------------------------------------|
|                           |                            |                                                                                                                                                                                                                             |                                             |                                | EAG or<br>GC-EAD                              | Y 型嗅觉实验或<br>室内网笼实验<br>Y-tube or<br>Laboratory | 田间试验<br>Field<br>bioassays |                                         |
| 按实蝇属<br><i>Anastrepha</i> | 西印度实蝇<br><i>A. obliqua</i> | 丁酸乙酯 Ethyl butyrate; 丁酸异丙酯<br>Isopropyl butyrate; 己醇 Hexan-1-ol; 丁<br>酸丙酯 Propyl butyrate; 丁酸异丁酯<br>Isobutyl butyrate; 己酸乙酯 Ethyl<br>hexanoate; 丁酸异戊酯 Isopentyl<br>butyrate; 苯甲酸乙酯 Ethyl benzoate; 辛<br>酸乙酯 Ethyl octanoate | Mombin fruit                                | ♀♂                             |                                               | +                                             |                            | Cruz-López <i>et al.</i> ,<br>2006      |
|                           |                            | 月桂烯 Myrcene; α-蒎烯 α-pinene; β-<br>罗勒烯 β-ocimene                                                                                                                                                                             | Amate mango; Coche<br>mango; Ataulfo mango; | ♀♂                             |                                               |                                               | +                          | Malo <i>et al.</i> , 2012               |
| 果实蝇属<br><i>Bactrocera</i> | 橘小实蝇<br><i>B. dorsalis</i> | 甲基丁香酚 Methyl eugenol                                                                                                                                                                                                        | 香茅<br><i>Cymbopogon citratus</i>            | ♂                              |                                               | +                                             |                            | Howlett, 1912a,<br>1912b                |
|                           |                            | 乙醇 Ethanol; 乙酸乙酯 Ethyl acetate;<br>己酸乙酯 Ethyl hexanoate; 乙酸己酯<br>Hexyl acetate; 壬酸芳樟酯 Linalyl<br>acetate; 壬酸乙酯 Ethyl nonanate; 乙酸<br>壬酯 Nonyl acetate; 肉桂酸乙酯 Ethyl<br>cinnamate; (E)-β-法尼烯 (E)-β-farnesene                  | 榄仁树<br><i>Terminalia catappa</i>            | ♀♂                             | +                                             | +                                             | +                          | Siderhurst <i>et al.</i> ,<br>2006      |
|                           |                            | 3- 萜烯 3-carene; β- 石竹烯<br>β-caryophyllene; α-葎草烯 α-humulene                                                                                                                                                                 | 番石榴 Guava;<br>芒果 Mango                      | ♀                              |                                               | +                                             |                            | Jaleel <i>et al.</i> , 2019             |
|                           |                            | 3- 甲基丁酸甲酯 Methyl<br>3-methylbutanoate; 乙酸丁酯 Butyl<br>acetate; 3-甲基丁基乙酸酯 3-methylbutyl<br>acetate; 乙酸己酯 Hexyl acetate                                                                                                        | 菠萝蜜假种皮<br>Arils of jackfruit                | ♀♂                             | +                                             | +                                             | +                          | Kamala Jayanthi<br><i>et al.</i> , 2021 |

续表 2 (Table 2 continued)

| 实蝇属<br>Genera              | 实蝇种<br>Species              | 信息类化合物<br>Compounds                                                                                                                                                                                                                 | 物质来源<br>Sources                                                                | 行为效应 <sup>a</sup><br>Behaviour | 活性测定法 <sup>b</sup><br>Behavioural experiments |                                                                 |                            | 参考文献<br>References                         |
|----------------------------|-----------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------|--------------------------------|-----------------------------------------------|-----------------------------------------------------------------|----------------------------|--------------------------------------------|
|                            |                             |                                                                                                                                                                                                                                     |                                                                                |                                | EAG or<br>GC-EAD                              | Y 型嗅觉实验或<br>室内网笼实验<br>Y-tube or<br>Laboratory<br>cage bioassays | 田间试验<br>Field<br>bioassays |                                            |
| 果实蝇属<br><i>Bactrocera</i>  | 番石榴实蝇<br><i>B. correcta</i> | 3- 萜烯 3-carene ; $\beta$ - 石竹烯<br>caryophyllene; $\alpha$ -律草烯 $\alpha$ -humulene                                                                                                                                                   | 番石榴 Guava;<br>芒果 Mango                                                         | ♀                              |                                               | +                                                               |                            | Jaleel <i>et al.</i> , 2019                |
|                            | 桃实蝇<br><i>B. zonata</i>     | 甲基丁香酚 Methyl eugenol                                                                                                                                                                                                                | 香茅<br><i>Cymbopogon citratus</i>                                               | ♂                              |                                               | +                                                               |                            | Howlett, 1912a,<br>1912b                   |
|                            | 柑橘大实蝇<br><i>B. minax</i>    | 壬醛 Nonanal; 柠檬醛 Citral; 柠檬烯<br>Limonene; 芳樟醇 Linalool                                                                                                                                                                               | 冰糖橙<br>Bingtang sweet oranges;<br>蜜桔<br>Satsumas mandarins;<br>酸橙 Sour oranges | ♀                              |                                               | +                                                               |                            | Liu and Zhou,<br>2016                      |
|                            | 昆士兰实蝇<br><i>B. tryoni</i>   | 香叶酸甲酯 Methyl geranate; 辛酸乙酯<br>Ethyl octanoate ; 己酸乙酯 Ethyl<br>hexanoate ; (Z)-3-己烯基丁酸酯 (Z)-3-<br>hexenyl butyrate; 苯甲酸甲酯 Methyl<br>benzoate; 苯甲酸异丁酯 Isobutyl benzoate                                                              | 橘子 Orange;<br>樱桃番石榴<br>Cherry guava;<br>香蕉 Banana;<br>斐济果 Feijoa fruit         | ♀                              | +                                             |                                                                 |                            | Mas <i>et al.</i> , 2020                   |
| 皱果实蝇属<br><i>Zeugodacus</i> | 瓜实蝇<br><i>Z. cucurbitae</i> | 覆盆子酮<br>4-(4-Hydroxyphenyl)-2-butanone                                                                                                                                                                                              | 兰花 Orchids                                                                     | ♂                              |                                               | +                                                               | +                          | Howse and<br>Underwood,<br>2000; Tan, 2009 |
|                            | 瓜实蝇<br><i>Z. cucurbitae</i> | (Z)-6-壬烯醛 (Z)-6-nonenal; (Z)-6-壬烯<br>-1-醇 (Z)-6-nonen-1-ol; 1-辛烯-3-醇<br>1-octen-3-ol; 乙酸 Acetic acid; (E,Z)-2,6-<br>壬二烯醛 (E,Z)-2,6-nonadienal; (E)-2-壬<br>烯醛 (E)-2-nonenal; 己醛 Hexanal; (E)-<br>2-辛烯醛 (E)-2-octenal; 1-己醇 1-hexanol | 黄瓜<br>Cucumber                                                                 | ♀                              | +                                             | +                                                               | +                          | Siderhurst and<br>Jang, 2010               |

续表 2 (Table 2 continued)

| 实蝇属<br>Genera              | 实蝇种<br>Species              | 信息类化合物<br>Compounds                                                                                                                                                                                                                      | 物质来源<br>Source                                                                                                       | 行为效应 <sup>a</sup><br>Behaviour | 活性测定法 <sup>b</sup><br>Behavioural experiments |                                                                 |                            | 参考文献<br>References             |
|----------------------------|-----------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|--------------------------------|-----------------------------------------------|-----------------------------------------------------------------|----------------------------|--------------------------------|
|                            |                             |                                                                                                                                                                                                                                          |                                                                                                                      |                                | EAG or<br>GC-EAD                              | Y 型嗅觉实验或<br>室内网笼实验<br>Y-tube or<br>Laboratory<br>cage bioassays | 田间试验<br>Field<br>bioassays |                                |
| 皱果实蝇属<br><i>Zeugodacus</i> | 瓜实蝇<br><i>Z. cucurbitae</i> | $\alpha$ -蒎烯 $\alpha$ -pinene; 1-辛烯-3-醇 1-octen-3-ol; 对伞花烃 P-cymene; 对乙基苯甲醛 P-ethyl-benzaldehyde; 水杨酸甲酯 Methyl salicylate; 对伞花烃-7-醇 P-cymen-7-ol                                                                                         | 丝瓜<br>Ridge gourd                                                                                                    | ♀                              | +                                             | +                                                               |                            | Shivaramu <i>et al.</i> , 2022 |
|                            |                             | $\alpha$ -蒎烯 $\alpha$ -Copaene                                                                                                                                                                                                           | 荔枝 <i>Litchi chinensis</i> ;<br>垂叶榕<br><i>Ficus benjamina</i> ;<br>鳄梨 <i>Avocado</i> ;<br>鳄梨 <i>Persea americana</i> | ♂                              | +                                             |                                                                 | +                          | Niogret <i>et al.</i> , 2011   |
| 蜡实蝇属<br><i>Ceratitis</i>   | 地中海实蝇<br><i>C. capitata</i> | 3-甲基丁烷-1-醇 3-methylbutan-1-ol; 1-辛烯-3-醇 1-octen-3-ol; $\beta$ -香叶烯 $\beta$ -caryophyllene                                                                                                                                                | 开花山茱萸<br>(北美山茱萸)<br>Flowering dogwood<br>( <i>Cornus florida</i> )                                                   | ♀♂                             |                                               | +                                                               |                            | Nojima <i>et al.</i> , 2003    |
|                            |                             | 丁酸丁酯 Butyl butanoate; 己酸丙酯 Propyl hexanoate; 己酸丁酯 Butyl hexanoate; 丁酸己酯 Hexyl butanoate; 己酸戊酯 Pentyl hexanoate                                                                                                                           | 苹果品种<br>Apple: Empire, Crispin, Cortland, Macintosh, Red Delicious                                                   | ♀♂                             | +                                             | +                                                               | +                          | Zhang <i>et al.</i> , 1999     |
| 绕实蝇属<br><i>Rhagoletis</i>  | 苹果实蝇<br><i>R. pomonella</i> | 3-甲基丁烷-1-醇 3-methylbutan-1-ol; 二氢- $\beta$ -丙酮 Dihydro- $\beta$ -ionone                                                                                                                                                                  | 绒毛红山楂<br>Downy red hawthorn<br>( <i>Crataegus mollis</i> )                                                           | ♀♂                             |                                               | +                                                               |                            | Cha <i>et al.</i> , 2018       |
|                            |                             | 3-甲基丁烷-1-醇 3-methylbutan-1-ol; 二甲基三硫 Dimethyl trisulfide; 1-辛烯-3-醇 1-octen-3-ol; 月桂烯 Myrcene; 壬醛 Nonanal; 芳樟醇 Linalool; (3E)-4, 8-二甲基-1, 3, 7-壬三烯 (3E)-4, 8-dimethyl-1, 3, 7-nonatriene; 癸醛 Decanal; $\beta$ -石竹烯 $\beta$ -caryophyllene | 雪莓果 Snowberry fruit                                                                                                  | ♀♂                             |                                               | +                                                               |                            | Cha <i>et al.</i> , 2017       |

有明显引诱效果 (Howlett *et al.*, 1912a, 1912b)。随后研究发现甲基丁香酚存在于白鹤芋属 *Spathiphyllum cannaefolium* 花 (Chuah *et al.*, 1996)、丁香 (Qin *et al.*, 2015)、细辛 (Liu *et al.*, 2021) 等在内的 400 多种植物中 (Tan and Nishida, 2012), 并相继发现甲基丁香酚对香蕉实蝇 *B. musae*、芒果实蝇 *B. occipialis*、菲律宾实蝇 *B. philippinensis* 等 81 种实蝇均有显著引诱效果 (IAEA, 2003; Tan and Nishida, 2012; Cáceres *et al.*, 2018); 兰花挥发物中覆盆子酮对瓜实蝇 *Z. cucurbitae* 雄虫有显著引诱效果 (Howse and Underwood, 2000), 而 Casanaginer 等 (2003) 通过大量实验筛选出引诱效果更好的衍生化合物 4-(对乙酰氧基苯基)-2-丁酮 (诱蝇酮, 覆盆子酮乙酸酯, Cue-lure, CL), 其对近 50 多种实蝇均有引诱作用 (IAEA, 2003), 目前甲基丁香酚和诱蝇酮已经被广泛用于实蝇监测防治 (IAEA, 2003)。

寄主植物果实挥发物对实蝇具有引诱效果。大量研究发现, 墨西哥按实蝇 *A. ludens*、番石榴实蝇 *B. correcta*、苹果实蝇 *R. pomonella*、地中海实蝇 *C. capitata*、橘小实蝇 *B. dorsalis* 及柑橘大实蝇 *B. minax* 等实蝇对寄主植物气味有趋向行为反应, 其中酯类、醇类、醛类、酸类、烯烃类以及萜类化合物能够引起实蝇的电生理反应, 室内引诱活性测定试验证实其对实蝇有强烈的引诱效果 (Niogret *et al.*, 2011; Robacker *et al.*, 2011; Liu and Zhou, 2016; Cha *et al.*, 2018; Jaleel *et al.*, 2019; Kamala Jayanthi *et al.*, 2021)。发酵佛手瓜挥发物中的 1,8-桉叶素、己酸乙酯、己醇、辛酸乙酯、苯甲酸乙酯、4-萜品醇、(-)- $\alpha$ -立方体苯及  $\alpha$ -萜品醇对墨西哥实蝇 *A. ludens* 雌雄虫均有引诱效果 (Robacker *et al.*, 1990, 1992); 苹果挥发物丁酸丁酯、己酸丙酯、己酸丁酯、丁酸己酯和己酸戊酯混合物对苹果实蝇 *R. pomonella* 有显著引诱效果 (Zhang *et al.*, 1999); 芒果挥发物月桂烯、 $\alpha$ -蒎烯和  $\beta$ -罗勒烯对西印度按实蝇 *A. obliqua* 有显著引诱效果 (Malo *et al.*, 2012); 番石榴和芒果挥发物中 3-萜烯、 $\beta$ -石竹烯、 $\alpha$ -萜

草烯在室内试验中对橘小实蝇 *B. dorsalis* 雌性显著引诱效果 (Jaleel *et al.*, 2019), 而菠萝蜜假种皮挥发物 3-甲基丁酸甲酯、乙酸丁酯、3-甲基丁基乙酸酯和乙酸己酯混合物对橘小实蝇 *B. dorsalis* 雌、雄虫均有显著引诱效果 (Kamala Jayanthi *et al.*, 2021)。综上所述, 来源于实蝇偏好寄主植物的挥发物成分是潜在信息化合物, 然而基于寄主植物挥发物所开发的引诱剂在实蝇田间实际应用较少, 无法达到有效控制实蝇危害的目的, 这也从另一方面说明挥发物生物活性尚不稳定, 仍需要对其作用机制进行深入研究, 从而破解田间效果不稳定的难题。

### 3 实蝇的其他来源信息化合物

自然界中, 昆虫与真菌之间存在着普遍的联系 (Jonsell and Nordlander, 2004), 真菌在昆虫的取食、交配等行为中存在一定影响 (Guo *et al.*, 2022; Meng *et al.*, 2022)。研究报道, 昆虫体内的微生物群产生的挥发性化合物在昆虫间的化学交流中发挥着重要作用, 如参与昆虫信息化合物的生产过程 (Engl and Kaltenpoth, 2018; Calcagnile *et al.*, 2019)。

实蝇体内的肠道菌等微生物能产生信息化合物 (表 3)。橘小实蝇 *B. dorsalis* 雄虫直肠中的芽孢杆菌, 可协助雄虫合成对雌虫具有显著引诱效果的三甲基吡嗪 (2,3,5-trimethylpyrazine, TMP) 和四甲基吡嗪 (2,3,5,6-tetramethylpyrazine, TTMP) (Ren *et al.*, 2021)。此外实蝇肠道菌的代谢物也具有潜在引诱力, 如橘小实蝇 *B. dorsalis* 肠道中的蜡样芽孢杆菌的代谢产物经室内外活性测试表明对橘小实蝇成虫具有显著引诱力 (Wang *et al.*, 2014)。同样酵母菌株挥发物中的异戊醇对橄榄实蝇 *B. oleae* 具有高引诱力, 并在田间引诱试验中明确对其橄榄实蝇 *B. oleae* 成虫有显著引诱效果 (Vitanović *et al.*, 2020)。张栩浩 (2022) 从实蝇危害的果实和寄主植物叶片中分离的酵母菌, 田间试验筛选出对南亚果实蝇 *Z. tau*、橘小实蝇 *B. dorsalis* 具有高引诱力的菌株, 为进一步发掘信息化合物奠定基础。

表 3 其他来源实蝇信息化合物  
Table 3 Semiochemicals of Tetrphitidae from others

| 实蝇属<br>Genera              | 实蝇种<br>Species              | 信息类化合物<br>Compounds                                                                                                                                                                               | 物质来源<br>Sources                                                                                                                          | 行为效应 <sup>a</sup><br>Behaviour | 活性测定法 <sup>b</sup><br>Behavioural experiments |                                                       |                         | 参考文献<br>References     |
|----------------------------|-----------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------|-----------------------------------------------|-------------------------------------------------------|-------------------------|------------------------|
|                            |                             |                                                                                                                                                                                                   |                                                                                                                                          |                                | EAG or GC-EAD                                 | Y 型嗅觉实验或室内网笼实验<br>Y-tube or Laboratory cage bioassays | 田间试验<br>Field bioassays |                        |
| 按实蝇属<br><i>Anastrepha</i>  | 墨西哥实蝇<br><i>A. ludens</i>   | 吡嗪<br>Indole; 2, 5-二甲基吡嗪 2,5-dimethylpyrazine; 2-苯乙醇 phenylethanol                                                                                                                                | 来自墨西哥实蝇 <i>A. ludens</i> 中肠的肠杆菌<br>Enterobacter agglomerans isolated from the midgut of wild <i>A. ludens</i>                            | ♀♂                             |                                               | +                                                     |                         | Robacker et al., 2004  |
|                            |                             | 三甲基吡嗪 2,3,5-trimethylpyrazine (TMP); 四甲基吡嗪 2,3,5,6-tetramethylpyrazine (TTMP)                                                                                                                     |                                                                                                                                          |                                |                                               |                                                       |                         |                        |
| 果实蝇属<br><i>Bactrocera</i>  | 橘小实蝇<br><i>B. dorsalis</i>  | 异戊醇 Isoamyl alcohol                                                                                                                                                                               | 来自橘小实蝇 <i>B. dorsalis</i> 雄性直肠中的芽孢杆菌<br>Bacillus species isolated from the <i>B. dorsalis</i> male rectum                                | ♀                              | +                                             |                                                       |                         | Ren et al., 2021       |
|                            |                             | 氨 Ammonia; 二甲基二硫醚 Dimethyl disulphide; 甲氧基苯基胂 Methoxy phenyl oxime; 2,2-二羟基-1-苯基乙酮 2,2-dihydroxy-1-phenyl ethenone; 1,2-苯二甲酸的丁基-2-甲基丙酯 Butyl-2-methylpropyl ester of 1,2-benzenedicarboxylic acid | 酵母菌株<br>Yeast strains                                                                                                                    | ♀♂                             |                                               | +                                                     | +                       | Vitanović et al., 2020 |
| 皱果实蝇属<br><i>Zeugodacus</i> | 瓜实蝇<br><i>Z. cucurbitae</i> |                                                                                                                                                                                                   | 来自瓜实蝇肠道和产卵器的肺炎克雷伯菌和阴沟肠杆菌<br><i>Klebsiella pneumoniae</i> and <i>Enterobacter cloacae</i> from gut and ovipositor of <i>Z. cucurbitae</i> | ♀♂                             |                                               | +                                                     |                         | Sajan et al., 2022     |

## 4 实蝇信息化合物应用进展

引诱剂诱杀是实蝇综合防治中的常用方法,可以有效监测和预警害虫爆发,同时还能与化学药剂 (Toyzhigitova *et al.*, 2019)、诱捕器 (Piñero *et al.*, 2006; 张宏宇, 2016)、诱虫灯 (张宏宇, 2018) 等其它技术结合使用,并在实际应用中选择最佳诱杀点 (李杖黎等, 2012b),最大化诱剂诱杀效果。当前用于实蝇监测防治应用的饵剂主要是食物饵剂 (Mazor *et al.*, 1987; Bateman and Morton, 1991; 杜迎刚等, 2017) 和信息化化合物饵剂如实蝇性信息素饵剂 (Heuskin *et al.*, 2011)、植物源信息化合物诱剂 (梁丹辉等, 2016)。由于信息化合物具有选择性好、活性高和使用量少等优势,广泛用于对实蝇的监测和田间防治 (Heuskin *et al.*, 2011; Park *et al.*, 2020),如基于 ME、CL 等信息化合物研制的实蝇高效饵剂 (Economopoulos and Haniotakis, 2019; Ballo *et al.*, 2020)。田间应用中,信息素化合物表现出高效引诱特性,但因其易挥发、持效期短的缺点,极大降低了应用效果,因此实蝇信息化合物开发应用中如何延长持效期是亟需解决的关键问题 (赵锦年等, 2011; 李运娜, 2018)。

缓释技术是延缓信息化合物释放速度和持效期的有效手段。通过特定材料或方法控制昆虫信息化合物缓慢释放,能有效防治虫害,减少农药使用,降低环境污染和农业成本 (严力等, 2019)。利用层状氢氧化锌作为载体材料开发了昆虫信息素己烯酸的控释配方,延缓信息素释放速率 (Ahmad *et al.*, 2015); 将信息素 1, 7-二氧螺环 5.5 十一烷封装成聚 L-乳酸微粒,显著延长其持效期至四周 (Zisopoulou *et al.*, 2020); 基于信息素月桂烯开发的正十八烷壳聚糖复合膜,具有良好的控释效果的同时还能依据昆虫的昼夜节律有规律性释放 (Li *et al.*, 2022)。传统缓释技术主要有固体信息素制剂、微胶囊、缓释微球等 (陈秀琴等, 2021; 李学琳, 2021; 马涛等, 2022), 其中固体材料制剂应用广泛。如凝胶类制剂 (李文芳, 2017; 马海泉, 2021)、无机吸

附材料 (李运娜, 2018)、浸渍绳、PVC 管 (相会明等, 2022)、橡胶芯等材料结合信息化合物通过包裹或模压制成缓释饵剂 (Golub *et al.*, 1983; Møttus *et al.*, 1997; Atterholt *et al.*, 1999; Johansson *et al.*, 2001; Selina *et al.*, 2008)。在实蝇缓释技术中,主要应用于甲基丁香酚、诱蝇酮等信息化合物。如基于 ME 和 Cue-lure 两种活性物质开发的水凝胶缓释剂对橘小实蝇 *B. dorsalis*、南亚果实蝇 *Z. tau* 具有良好的引诱效果 (马海泉, 2021)。随着纳米技术发展,具有缓释特性的纳米材料不断应用于信息化合物的缓释剂型研究中。糠醇胺-介孔二氧化硅材料对甲基丁香酚进行改性,研制出效果好、寿命长的环保型缓释剂,为信息化合物缓释剂型研究提供新的方向 (Chen *et al.*, 2019, 2020)。目前市面上,基于信息素开发的产品有北京中捷四方生物科技有限公司生产橘小实蝇 *B. dorsalis* 诱芯、瓜实蝇 *Z. cucurbitae* 诱芯和地中海实蝇 *C. capitata* 诱芯 (<http://www.youbuqi.cn/chanpin/syyx/310.html>), 南京新安中绿生物科技有限公司生产的橘小实蝇 *B. dorsalis* 膏剂 (胶条) 和柑橘大实蝇 *B. minax* 膏剂 (<http://www.smartagri.bio.com>) 等产品 (表 4)。

此外,信息化合物还能与物理防控如色板、灯光诱杀,化学农药和其他饵剂如食物饵剂结合使用,发挥各自优势,提高害虫防治效果 (林明光等, 2013; 王波等, 2013; 郭峰等, 2020)。3%甲氨基阿维菌素苯甲酸盐与甲基丁香酚混配使用显著增强橘小实蝇 *B. dorsalis* 的诱杀效果 (张艳等, 2013); Naled 90% : 甲基丁香酚 = 20% : 80% 的配比获得的诱杀剂对桃实蝇 *B. zonta* 诱杀效果显著优于其他杀虫剂,且对桃实蝇 *B. zonata* 有效防控时期长达 8 周 (Ghanim *et al.*, 2010)。此外市面上有北京中捷四方生物科技有限公司、漳州英格尔科技公司等生产的实蝇信息素粘虫板产品 (陈海燕等, 2018)。总而言之,信息化合物在实际应用中与多种措施结合可提高诱杀效果,是信息化合物应用于实蝇害虫绿色防控和综合治理的重要方向。

表 4 已用于实蝇监测与防治的实蝇信息化合物及其产品  
Table 4 Semiochemicals and products used for monitoring and controlling Tetrphitidae

| 信息化合物<br>Compounds                                | 饵剂<br>Lures                                                                     | 防治对象<br>Insect pests                                                                                                                                                                                                                                                                                                                                        | 生产公司或参考文献<br>Companies or references                                       |
|---------------------------------------------------|---------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------|
| 4-烯丙基-1,2-二甲氧基苯<br>4-Allyl-1,2-dimethoxybenzene   | 诱蝇醚 ME<br>Methyl eugenol                                                        | 杨桃实蝇 <i>B. carambolae</i> ; 胡桃实蝇 <i>B. caryae</i> ; 番石榴实蝇 <i>B. correcta</i> ; 橘小实蝇 <i>B. dorsalis</i> ; 斯里兰卡实蝇 <i>B. kandiensis</i> ; 香蕉实蝇 <i>B. musae</i> ; 芒果实蝇 <i>B. occipitalis</i> ; 木瓜实蝇 <i>B. papayae</i> ; 菲律宾实蝇 <i>B. philippinensis</i> ; 瘤胫实蝇 <i>B. tuberculata</i> ; 三带实蝇 <i>B. umbrosa</i> ; 黄侧条实蝇 <i>B. xanthodes</i> ; 桃实蝇 <i>B. zonata</i> | Pipef, 2002                                                                |
|                                                   | 橘小实蝇引诱剂<br>Attractants of <i>B. dorsalis</i>                                    | 橘小实蝇 <i>B. dorsalis</i>                                                                                                                                                                                                                                                                                                                                     | 中捷四方 (北京) 生物科技有限公司<br>Beijing Pherobio Technology Co., Ltd.                |
|                                                   | 橘小实蝇膏剂/胶条<br>(诱芯) Ointment /<br>gum strips (lure core)<br>of <i>B. dorsalis</i> | 橘小实蝇 <i>B. dorsalis</i>                                                                                                                                                                                                                                                                                                                                     | 南京新安中绿生物科技有限公司<br>Nanjing Xinan SinoGreen Biological<br>Technology Co. Ltd |
|                                                   | 柑橘小实蝇引诱剂<br>Attractants of <i>B. dorsalis</i>                                   | 橘小实蝇 <i>B. dorsalis</i>                                                                                                                                                                                                                                                                                                                                     | 河南爱树科技发展有限公司<br>Henan LoveTree Technology Development<br>Co.,Ltd           |
|                                                   | 橘小实蝇诱芯<br>Attractants of <i>B. dorsalis</i>                                     | 橘小实蝇 <i>B. dorsalis</i>                                                                                                                                                                                                                                                                                                                                     | 北京依科曼生物技术股份有限公司<br>Beijing Ecoman Biological Technology Co.<br>Ltd         |
|                                                   | 橘小实蝇诱芯<br>Attractants of <i>B. dorsalis</i>                                     | 橘小实蝇 <i>B. dorsalis</i>                                                                                                                                                                                                                                                                                                                                     | 泉州市绿普森生物科技有限公司<br>Quanzhou Lvpusen Biotech Co., Ltd.                       |
| (R)-(+)-柠檬烯<br>(R)-(+)-Limonene                   | (R)-(+)-柠檬烯<br>(R)-(+)-Limonene                                                 | 柑橘大实蝇 <i>B. minax</i>                                                                                                                                                                                                                                                                                                                                       | 张宏宇, 2015; 李运娜, 2018                                                       |
| 4-(乙酰氧基苯基)-2-丁酮<br>4-(p-Acetoxyphenyl)-2-butanone | 瓜实蝇引诱剂<br>Attractants of<br><i>Z. cucurbitae</i>                                | 瓜实蝇 <i>Z. cucurbitae</i>                                                                                                                                                                                                                                                                                                                                    | 河南爱树科技发展有限公司<br>Henan LoveTree Technology Development<br>Co.,Ltd           |
|                                                   | 瓜实蝇膏剂 (诱芯)<br>Ointment / gum strips<br>(lure core) of<br><i>Z. cucurbitae</i>   | 瓜实蝇 <i>Z. cucurbitae</i>                                                                                                                                                                                                                                                                                                                                    | 南京新安中绿生物科技有限公司<br>Nanjing Xinan SinoGreen Biological<br>Technology Co. Ltd |
|                                                   | 瓜实蝇引诱剂<br>Attractants of<br><i>Z. cucurbitae</i>                                | 瓜实蝇 <i>Z. cucurbitae</i>                                                                                                                                                                                                                                                                                                                                    | 中捷四方 (北京) 生物科技有限公司<br>Beijing Pherobio Technology Co., Ltd.                |

续表 4 (Table 4 continued)

| 信息化化合物<br>Compounds                                                        | 饵剂<br>Lures                                      | 防治对象<br>Insect pests                                                                                                                                                                                                  | 生产公司或参考文献<br>Companies or references                            |
|----------------------------------------------------------------------------|--------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------|
| 4-(乙酰氧基苯基)-2-丁酮<br>4-(p-Acetoxyphenyl)-2-butanone                          | 诱蝇酮 CL<br>Cue-lure                               | 瓜实蝇 <i>Z. cucurbitae</i> ; 大洋洲橘实蝇 <i>B. curvipennis</i> ; 汤加实蝇 <i>B. facialis</i> ; 基尔基实蝇 <i>B. kiriki</i> ; 小昆士兰实蝇 <i>B. neohumeralis</i> ; 斐济实蝇 <i>B. passiflorae</i> ; 昆士兰实蝇 <i>B. tryoni</i> ; 南瓜实蝇 <i>Z. tau</i> | Pipef, 2002                                                     |
| 2-甲基-4-氯环己烷羧酸特丁基酯<br>Tert-butyl 4-chloro-2-methylcyclohexane-1-carboxylate | 瓜实蝇诱芯<br>Lure core of<br><i>Z. cucurbitae</i>    | 瓜实蝇 <i>Z. cucurbitae</i>                                                                                                                                                                                              | 北京依科曼生物技术股份有限公司<br>Beijing Ecoman Biological Technology Co. Ltd |
|                                                                            | 地中海实蝇引诱剂<br>Attractants of<br><i>C. capitata</i> | 地中海实蝇 <i>C. capitata</i>                                                                                                                                                                                              | 中捷四方(北京)生物科技有限公司<br>Beijing Pherobio Technology Co., Ltd.       |
| $\alpha$ -紫罗兰醇<br>$\alpha$ -Ionol                                          | TML (trimedlure)                                 | 纳塔尔实蝇 <i>C. rosa</i> ; 马斯卡林实蝇 <i>C. catoirii</i>                                                                                                                                                                      | Pipef, 2002                                                     |
| 碳酸氢铵<br>Ammonium Bicarbonate                                               | Latilure                                         | 辣椒实蝇 <i>B. latifrons</i>                                                                                                                                                                                              | Pipef, 2002                                                     |
|                                                                            | 碳酸氢铵<br>Ammonium Bicarbonate                     | 橄榄实蝇 <i>B. oleae</i> ;<br>苹果实蝇 <i>R. pomonella</i>                                                                                                                                                                    | Pipef, 2002                                                     |
| 螺酮缩醇(1,7-二旋氧杂[5.5]十一烷) 1,7-Dioxaspiro(5.5)undecane                         | 螺环缩酮<br>Spiroketal                               | 橄榄实蝇 <i>B. oleae</i>                                                                                                                                                                                                  | Pipef, 2002                                                     |
| 乙酸铵<br>Ammonium acetate                                                    | 乙酸铵<br>Ammonium acetate                          | 西美绕实蝇 <i>R. indifferens</i> ; 黑樱桃实蝇 <i>R. fausta</i> ;<br>核桃壳实蝇 <i>R. completa</i> ; 东部樱桃实蝇 <i>R. cingulata</i> ;<br>欧洲樱桃实蝇 <i>R. cerasi</i>                                                                          | Pipef, 2002                                                     |
| 乙酸松油酯<br>$\alpha$ -terpinyl acetate                                        | 乙酸松油酯<br>Terpinyl acetate                        | 非洲芒果实蝇 <i>C. cosyra</i>                                                                                                                                                                                               | Pipef, 2002                                                     |
| 己酸丁酯<br>Butyl hexanoate                                                    | 己酸丁酯<br>Butyl hexanoate                          | 苹果实蝇 <i>R. pomonella</i>                                                                                                                                                                                              | Pipef, 2002                                                     |
| 碳酸铵<br>Ammonium carbonate                                                  | 碳酸铵<br>Ammonium carbonate                        | 欧洲樱桃实蝇 <i>R. cerasi</i> ; 东部樱桃实蝇 <i>R. cingulata</i> ;<br>黑樱桃实蝇 <i>R. fausta</i> ; 西美绕实蝇 <i>R. indifferens</i>                                                                                                        | Pipef, 2002                                                     |

## 5 展望

实蝇信息化合物在实蝇监测和防治工作中发挥着重要的作用(李咏玲等, 2010; Scolari *et al.*, 2021)。当前实蝇信息化合物研究多着眼于虫体、寄主植物等, 而寄主植物挥发物中被证实有效的物质多为混合物(Kamala Jayanthi *et al.*, 2021), 效果不稳定、应用难度大, 阻碍了实蝇信息化合物的推广应用。未来研究中, 从实蝇生态位或生物习性出发, 扩展信息化合物的来源, 如实蝇虫体排泄物和肠道菌等(Ren *et al.*, 2021; Scolari *et al.*, 2021), 或许有稳定的活性物质, 促进信息化合物的发掘。

目前实蝇信息化合物的活性研究多局限于室内实验, 是因为信息化合物在室外实验的效果不理想, 难以开展大田实验, 是亟待解决重点难题。由于室外温度、紫外线、雨水、大风等环境因素造成的影响, 导致信息化合物的持效期短, 效果差(Gallego *et al.*, 2008; Kaur *et al.*, 2021)。有研究表明利用物理缓释(李运娜 2018; 马海泉, 2021)、化学缓释(张瑜, 2017; Muskat and Patel, 2021)、纳米材料包裹(Chen *et al.*, 2020; Li *et al.*, 2022)等多种方式可显著提高信息化合物的持效期。此外, 与化学农药、物理防控技术和其他饵料相结合, 如甲基丁香酚和诱蝇酮这两种广泛用于实蝇防控的物质, 因其引诱雄性实蝇的专性特性(Beroza *et al.*, 1960; IAEA, 2003; Park *et al.*, 2020), 可在此基础上和其他对雌性有显著引诱能力的物质相结合, 开发雌雄双诱型诱剂, 达到“1+1>2”的效果(张艳等, 2013; Royer and Mayer, 2018; 张宏宇, 2018; 郭峰等, 2020)。因此, 未来研究应不断完善实蝇害虫综合防控体系, 提高实蝇防控效率, 保障果蔬产品经济效益。

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