Implementation of IPM programs on European greenhouse tomato production areas.

Tools and constraints

endure
diversifying crop protection

SIXTH FRAMEWORK PROGRAMME

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Implementation of IPM programs on European greenhouse tomato production areas: Tools and constraints

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Summary*

Whiteflies and whitefly-transmitted viruses are some of the major constraints on European tomato production. The main objectives of this study were to: identify where and why whiteflies are a major limitation on tomato crops; collect information about whiteflies and associated viruses; determine the available management tools; and identify key knowledge gaps and research priorities. This study was conducted within the framework of ENDURE (European Network for Durable Exploitation of Crop Protection Strategies).

Two whitefly species are the main pests of tomato in Europe: *Bemisia tabaci* and *Trialeurodes vaporariorum*. *Trialeurodes vaporariorum* is widespread to all areas where greenhouse industry is present, and *B. tabaci* has invaded, since the early 1990's, all the subtropical and tropical areas. Biotypes B and Q of *B. tabaci* are widespread and especially problematic. Other key tomato pests are *Aculops lycopersici, Helicoverpa armigera, Frankliniella occidentalis*, and leaf miners. Tomato crops are particularly susceptible to viruses causingTomato yellow leaf curl disease (TYLCD). High incidences of this disease are associated to high pressure of its vector, *B. tabaci.* The ranked importance of *B. tabaci* established in this study correlates with the levels of insecticide use, showing *B. tabaci* as one of the principal drivers behind chemical control. Confirmed cases of resistance to almost all insecticides have been reported. Integrated Pest Management based on biological control (IPM-BC) is applied in all the surveyed regions and identified as the strategy using fewer insecticides. Other IPM components include greenhouse netting and TYLCD-tolerant tomato cultivars. Sampling techniques differ between regions, where decisions are generally based upon whitefly densities and do not relate to control strategies or growing cycles. For population monitoring and control, whitefly species are always identified.

In Europe IPM-BC is the recommended strategy for a sustainable tomato production. The IPM-BC approach is mainly based on inoculative releases of the parasitoids *Eretmocerus mundus* and *Encarsia*

**See the glossary of technical terms about pests, diseases and pesticides residues at the end of the document.*

formosa and/or the polyphagous predators *Macrolophus caliginosus* and *Nesidiocoris tenuis*. However, some limitations for a wider implementation have been identified: lack of biological solutions for some pests, costs of beneficials, low farmer confidence, costs of technical advice, and low pest injury thresholds. Research priorities to promote and improve IPM-BC are proposed on the following domains: (i) emergence and invasion of new whitefly-transmitted viruses; (ii) relevance of *B. tabaci* biotypes regarding insecticide resistance; (iii) biochemistry and genetics of plant resistance; (iv) economic thresholds and sampling techniques of whiteflies for decision making; and (v) conservation and management of native whitefly natural enemies and improvement of biological control of other tomato pests.

1. Introduction

The present situation of tomato production in European growing areas and the tools used to manage key pests have been evaluated within the framework of ENDURE (European Network for Durable Exploitation of Crop Protection Strategies). The study was coordinated by UdL (Universitat de Lleida) and IRTA (Institut de Recerca i Tecnologia Agroalimentàries). Other participant organizations were RRES (Rothamsted Research); CIRAD (Centre de Coopération Internationale en Recherche Agronomique pour le Développement); INRA (Institut National de la Recherche Agronomique); WUR (Wageningen University Research Centre) and JKI (Julius Kühn-Institut- Bundesforschungsinstitut für Kulturpflanzen).

Whiteflies and whitefly-transmitted viruses (mostly a group of virus species causing Tomato yellow leaf curl disease) (TYLCD) are among the most severe pests and diseases in several European tomato-growing areas. The complexity of the problem, which includes distinct biotypes of whiteflies, variation within and between virus strains, increasing number of insecticide-resistant populations, and difficulties on biological control applications, has been one of the main subjects of cooperation between researchers and industrialists. For more information see IOBC/WPRS on “Integrated Control in Protected Crops, Mediterranean Climate" and "Integrated Control in Glasshouses".

The aim of the present study was to: a) identify tomato-growing areas where whiteflies are the major constraint to tomato production; b) collect information on the situation and biology of *Bemisia tabaci* and whitefly-transmitted viruses in the European Union (EU) and neighboring countries; c) determine the tools available to manage these pests on tomato; and d) evaluate the current implementation of Integrated Pest Management (IPM) programs on the different tomato-growing areas.

Photo 1. Greenhouses of the Campo de Dalías, Almería Province (Spain) showing the large density of greenhouses. © Photo from the Image Science&Analysis Laboratory, NASA Johnson Space Center; ISS008-E-14686; http//eol.jsc.nasa.gov).

2. Relevance of tomatoes in Europe: tomato production, trading and consumption

Tomato is the most widely grown vegetable. In 2005, 126 million tones of fresh tomato were produced in the world, harvested from 4.5 million ha (FAOSTAT 2007). The major producers were (in million tones): China (31.6), USA (11), Turkey (10) and India (8.6). The EU-27 produced 18 million tones with a hectarage of 0.3 million ha and a value share of about 25% of the total vegetables produced in Europe. Although grown throughout Europe, 92% of the total EU-27 fresh tomato production is harvested by seven leading producers (in million tones), mainly from the Mediterranean basin: Italy (7), Spain (4.5), Greece (1.7), Portugal (1.1), France (0.8), the Netherlands (0.7) and Poland (0.6) (Figure 1).

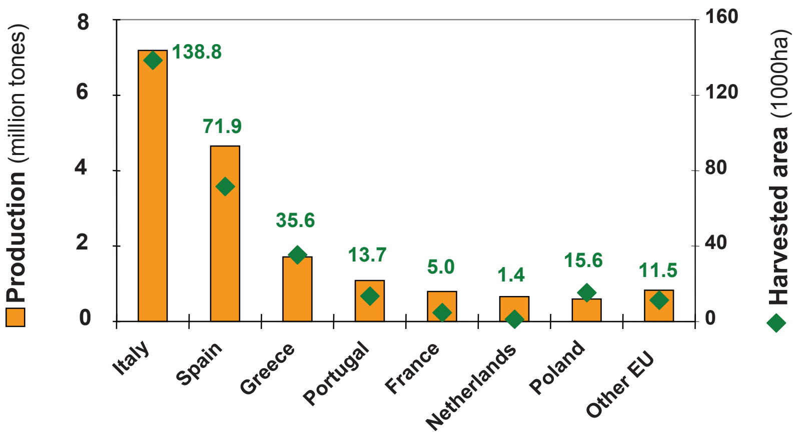


Figure 1. Main fresh tomato-producing countries in EU-27 in 2005 (FAOSTAT 2007), in terms of production (bars) and hectarage (green symbols and numbers).

Fresh tomato is one of the most consumed vegetables in Europe: 15 million tones in 2005 (93 g/capita and day), which represented a share of 80% of the total vegetables. Approximately 90% of the tomato consumed in EU is produced within EU, and only France imported a significant amount (47.5% of tomatoes sold in France) from non-EU countries: 91% from Morocco, 6% from Israel, and 3% from others.

The EU pesticide residue monitoring report conducted in 2004 (Commission of the European Communities, 2006) provided evidence of the absence of residues in 64% of tomato samples. Residues in 35% of tomato samples were at/or below the maximum residue level (MRL), national or EU, which indicates that pesticides have been used in the production process but pose no safety concerns for consumers. Only 1% of the tomato samples exceeded the statutory limits (MRL). Pesticide biodegradation in soil was 16-fold slower than in the plant (Juraske et al., 2008), suggesting that the use of pesticides has a greater impact on the environment than on food quality. Therefore, pesticide reduction could be a key tool for an environmentally sustainable tomato production.

3. Methodology

Data were gathered through two questionnaires. The first one was designed to collect information on the situation and ecology of *B. tabaci* and whitefly-transmitted viruses in EU and neighbouring countries, as well as the tools available to manage this pest on tomato. The second one studied the implementation of IPM programs on European tomato-growing areas.

In the first questionnaire, surveys from ten countries were analyzed: France, Germany, Greece, Israel, Italy, Morocco, Spain, The Netherlands, Turkey, and United Kingdom. Advisors, Plant Protection Services, and scientists answered a total of 32 questionnaires (Table 1). Data from the questionnaires represented very variable surface areas, ranging from 5 to 100% of the total tomato-harvested area for each country. The topics covered were: whitefly species, *B. tabaci* biotypes, insecticide resistance, whitefly-vectored virus species and hosts, whitefly natural enemies and their use in biological control, other control tools, and sampling techniques for decision making.

The second questionnaire was conducted in four tomato production areas that represented four different ***scenarios***, according to their different levels of *B. tabaci* pressure and incidence of whitefly-transmitted viruses and to growing conditions: (1) high *B. tabaci* pressure and whitefly-transmitted viruses (Almeria, southeast Spain), (2) medium *B. tabaci* pressure and whitefly-transmitted viruses, and tomato produced in non-heated greenhouses (Catalonia, northeast Spain), (3) medium *B. tabaci* pressure and whitefly-transmitted viruses, and tomato produced in heated greenhouses during winter (Roussillon, southeast France), and (4) low *B. tabaci* pressure and whitefly-transmitted viruses absent (Germany). In Catalonia a minor area with high *B.tabaci* populations and severe TYLCD problems was detected and considered separately (Catalonia#). Since open field tomato crops were present just in Catalonia, only surveys referring to greenhouse tomato production were processed.

Table 1. Number of questionnaires and surface area represented for each country. *** Percentage of surface was calculated on national area harvested in 2005, according to FAOSTAT (FAOSTAT, 2007). GLH = glasshouse, GRH = greenhouse, NH = net house and OF = open field crops. The questionnaire from United Kingdom reported no presence of *B. tabaci*

Country	No. question.	Surface (ha)	% surface ***	Tomato production		
				GLH	GRH/NH	OF
France	5	2450	49	▲	▲	▲
Germany	3	368	100	▲	▲	▲
Greece	2	2420	5	▲	▲	▲
Israel	2	20500	100		▲	▲
Italy	3	8500	6	▲	▲	▲
Morocco	2	4600	21		▲	▲
Spain	7	12500	17		▲	▲
Netherlands	3	1400	100	▲	▲	
Turkey	5	No data	No data	▲	▲	▲

Data from one area or scenario were grouped into three growing cycles that were defined according to the transplanting date and growing conditions: (A) transplant in early spring (mid-January to April), (B) transplant in summer (July to August) and (C) transplant in fall-winter (November to January) in heated greenhouses.

Four different pest control strategies were defined: Chemical or based only on the use of insecticides, IPM-Insecticide or integrated pest management strategy based on the rational application of insecticides, IPM-Biological control (BC) or integrated pest management strategy based on the use of natural enemies and selective pesticides, and Organic production based on an insecticide-free approach.

A single questionnaire was obtained for each scenario, crop cycle, and control strategy by interviewing several advisors operating in each of the four associated geographical regions. Topics covered included: main viruses and insect pests; sampling methods used for decision making; use of biological control, insecticides and other control methods; and constraints to a wider implementation of IPM strategies. Table 2 summarizes the surface area for each crop cycle and the pest control strategies within the regions covered on the survey.

Table 2. Growing cycles, surface area and pest control strategies for each scenario represented in the questionnaires answered by the advisors

Area		**Cycle**	**Surface (ha)**	**Pest control strategies**			
				Chemical	**IPM-Insct.**	**IPM-BC**	**Organic**
Germany		A	3			▲	▲
		C	17	▲	▲	▲	▲
Roussillon		A	20		▲	▲	▲
		B	30		▲		
		C	50		▲	▲	
Catalonia		A	30	▲	▲	▲	▲
		B	18	▲	▲	▲	▲
	#	A	17	▲	▲	▲	
		B	15	▲	▲	▲	
Almeria		A	3300	▲	▲	▲	
		B	6700		▲	▲	

4. Tomato crop cycles and main tomato pests

Tomato crop cycles in each selected scenario are represented in Figure 2. In the most common growing cycle (cycle A), present in the four areas, transplants occur from January to April (from south to north) and crops last until July-October. For cycle B, which is absent in Germany, transplants occur mostly during August and last until December in Catalonia (non-heated greenhouses), May in Almeria (non-heated greenhouses), and July in Roussillon (heated glasshouses). In Catalonia# cycle B extends to January, and consequently almost no free-crop period is left. Transplants in fall or winter (cycle C) only take place in France and Germany, where glasshouses with heating systems are present. In these conditions, harvest lasts until October or November. Tomato-free periods are absent in Roussillon but occur in winter in Germany and Catalonia and during summer in Almeria. Long cycles of continuous tomato crop (11 months) are present only in Germany and France.

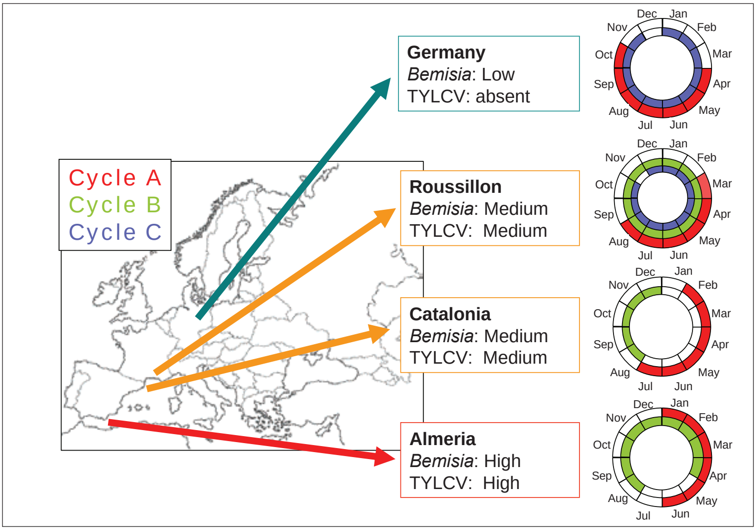


Figure 2. Different crop cycles present in each area.

Table 3. Main tomato pests by area and crop cycle classified according to their importance: 0= absent, 1= not very important, 2= important, and 3= very important. See figure 2 above for cycle description

Area	Cycle	*T. vaporariorum*	*B. tabaci*	*H. armigera*	*Liriomyza spp.*	*F. occidentalis*	*A. lycopersici*	*Tetranychus spp.*
Germany	A	3	1	0	2	1	1	1
	C	3	1	0	2	1	1	1
Roussillon	A	2	1	2	2	1	1	3
	B	3	3	1	2	3	1	2
	C	3	3	1	3	2	1	2
Catalonia	A	1	1	1	2	2	2	1
	B	2	2	3	1	2	3	1
Catalonia #	A	1	3	3	1	2	3	1
	B	0	3	3	1	2	3	1
Almeria	A	2	3	1	1	2	3	2
	B	1	3	1	1	3	3	2

Table 3 shows the incidence of pests in the different areas and crop cycles. The relative economic importance of individual pest species in different areas in Europe depends upon the local cultivation practices, the environment, and the crop cycles.

Two whitefly species are key pests of tomato. The first one, *Bemisia tabaci*, is capable of causing severe losses even at low densities due to the specific plant viruses it can transmit. These include some of the most damaging viruses affecting tomatoes, such as *Tomato yellow leaf curl virus* (TYLCV). The second one, *Trialeurodes vaporariorum*, also transmits plant viruses, e.g. *Tomato infectious chlorosis virus* (TICV), although they are of somewhat lesser economic impact. Since these two whitefly species can coexist within the same crop, correct identification is a prerequisite to efficient control. *Trialeurodes vaporariorum* is a serious problem in Germany and Roussillon, while *B. tabaci* has high importance in Roussillon, during cycles B and C, in Catalonia# and in Almeria. A great difference on *B. tabaci* incidence was recorded

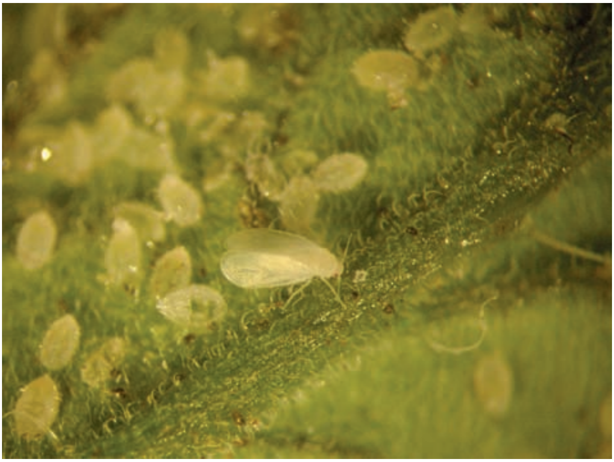


Photo 2. Nymphs and adult of *T. vaporariorum.* © Photo from IRTA Entomology.

Photo 3. Nymphs and adults of *B. tabaci.* © Photo from IRTA Entomology.

Photo 4. Larvae of *Frankliniella occidentalis*. © Photo from IRTA Entomology.

Photo 5. Symptoms of *Aculops lycopersici*. © Photo from J. Ariño, Selmar.

between Catalonia and Catalonia#, two very close areas with similar climatic conditions but different crop cycle duration. In Catalonia a clear crop-free period occurs in winter (approximately from the end of December to mid-February), whereas in Catalonia# the end of cycle B (end of January) moves closer to the beginning of cycle A (mid-January), enhancing the carry over of *B. tabaci* and viruses among old and young plants. In the other areas where *B. tabaci* is ranked as a very important pest, the tomato-free period is absent (Roussillon) or occurs during summer (Almeria), when conditions —climatic parameters and available host plants— for the survivorship of the pest are favourable.

Among other tomato pests, 5 are ranked as key pests in at least one area. The russet mite *Aculops lycopersici* is an increasingly harmful pest in the Mediterranean area, being a key problem in Spain; *Frankliniella occidentalis* is considered an important pest in all the areas except in Germany; *Helicoverpa armigera* is considered a very important pest of tomato production only in Catalonia during summer; leaf miners are ranked as important pests in Catalonia, Germany and Roussillon, mainly in the long growing cycles; and *Tetranychus spp.* is considered an important pest in Roussillon and Almeria.

5. Whiteflies: *Bemisia tabaci* and *Trialeurodes vaporariorum*

5.1. Distribution of whitefly species

Figure 3 collates the information on the distribution of *B. tabaci* as a pest of outdoor and greenhouse crops together with data on the distribution of whitefly species in tomato crops. *Bemisia* tabaci is widely distributed, although outdoors its northerly limit extends across southern France, southern Italy, around the northern coast of the Mediterranean Sea and across northern Turkey. Single infestations of *B. tabaci* are reported in some areas of Spain, Greece, Morocco and Turkey, and mixed infestations of both whitefly species are common in most of the tomato-growing areas, including some locations of Morocco and the Canary and Reunion Islands. Single populations of *T. vaporariorum* are usually found in northern locations of Europe (United Kingdom and north of Germany and France) and in an area of Turkey where tomatoes are grown only in open field. Therefore, the prevalence of *T. vaporariorum* is low in the south and increases northwards, while the prevalence of *B. tabaci* is low in the north and increases southwards.

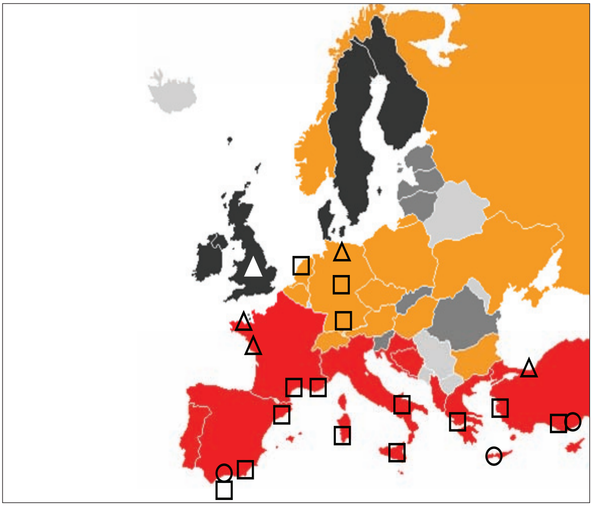


Figure 3. Distribution of whitefly species in tomato-growing areas in Europe and Mediterranean partner countries. Colours: ■ = outdoor and protected crops, ■ = primarily protected crops, ■ = absent or non-persistent, ■ = absent or non-persistent (protected zone), ■ = no information (Gorman, unpublished). Symbols represent: ○ = *B. tabaci*, △ = *T. vaporariorum* and □ = mixed populations of *B. tabaci* and *T. vaporariorum.*

5.2. Distribution of *Bemisia tabaci* biotypes

At least four biotypes of *B. tabaci* are currently present in Europe. Due to their invasive and damaging nature, the two most widespread and problematical within agricultural environments are biotypes B and Q, which also prevail within European tomato production. Biotypes B and Q are known to coexist in some areas, although they do not interbreed (Ma et al., 2004). Less widespread biotypes reported in Europe are biotype S, which has been identified only on *Ipomoea indica* in

Spain (Málaga) (Rua et al., 2006), and biotype T, identified only on *Euphorbia characias* in southern Italy and Sicily (Simon et al., 2003).

According to data collected in the first questionnaire, biotype Q is the most widespread biotype either on its own (11 locations) or mixed with biotype B (4 locations) (Figure 4). Single infestations of biotype B were reported for 6 locations.

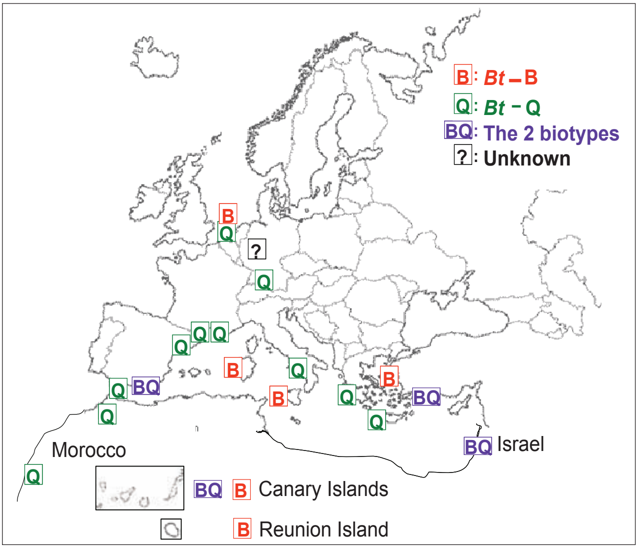


Figure 4. Distribution of *B. tabaci* biotypes in tomato-growing areas in Europe and Mediterranean partner countries.

6. Viruses transmitted by whiteflies and other insects

6.1. Viruses causing tomato yellow leaf curl disease

Bemisia tabaci causes severe crop losses due to the transmission of TYLCD. This disease is caused by a complex of virus species of the genus Begomovirus (family Geminiviridae). Tomato crops throughout the world, especially in warm temperate regions, are particularly susceptible to this group of viruses, being a limiting factor for cultivation (Cohen and Lapidot, 2007).

Figure 5 shows that TYLCD is present in all growing areas around the Mediterranean basin (EPPO 2006). According to data collected, TYLCD also damages other crops such as beans in some areas of Greece, peppers in Reunion Island, and ornamentals in Israel and mainland Italy.

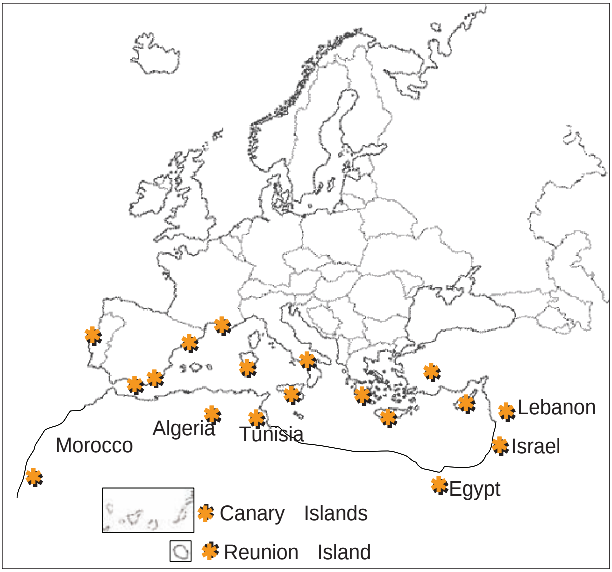


Figure 5. Distribution map of TYLCD (✱) in EU countries and the Mediterranean Basin (OEPP 2006).

The symptoms of yellow leaf curl disease in tomato —leaf curl, yellow mosaics, plant growth reduction, stunting and vein thickening (Anonymous, 2001)— can be caused by several geminiviruses and not only by the renowned *Tomato yellow leaf curl virus* (TYLCV). The two recombinant geminiviruses identified in Spain, *Tomato yellow leaf curl Malaga virus* and *Tomato yellow leaf curl Axarquia virus*, result from recombination events between the two geminiviruses known to cause TYLCD in Spain, which are TYLCV and *Tomato yellow leaf curl*

Sardinia virus (TYLCSV) (Monci et al., 2002, Garcia-Andres et al., 2006). In addition to these four geminivirus species identified in Europe, 50 more distinct geminiviruses have been described around the world and identified all in tomato (Abhary et al. 2007, and references therein). The risk associated to the introduction of some non-European tomato geminiviruses into Europe, is intensified by the possibility that these viruses may recombine with European viruses to produce new species.

Photo 6. Tomato plant affected by TYLCD.
© Photo from IRTA Entomology.

Comparison of data concerning virus importance and insect vector prevalence (Table 4) reveals that wherever the pressure of *B. tabaci* is high, viruses responsible for TYLCD are important or very important. This is particularly evident on the two surveyed sites in Catalonia: Catalonia#, a reduced horticultural area located in the south of Barcelona, has high *B. tabaci* pressure and shows very important TYLCD incidence; whereas Catalonia, with the majority of the tomato production in the northeast of Spain, has medium *B. tabaci* pressure and shows not very important TYLCD incidence.

Table 4. Correlation between importance of insect-transmittedviruses incidence and their vector. *B.t.= B. tabaci*, *T.v.= T. vaporariorum, F.o.= Frankliniella occidentalis.* Importance rank: 0= absent, 1=not very important, 2= important and 3= very important. See figure 2 for cycle description and the glossary for virus species names and descriptions

Area	Cycle	*B.t.*	TYLCV	ToCV	*T.v.*	TICV	*F. o.*	TSWV
Germany	A	1	0	0	3	0	1	1
	C	1	0	0	3	0	1	0
Roussillon	A	1	1	1	2	0	1	2
	B	3	3	2	3	0	3	3
	C	3	3	3	3	0	2	3
Catalonia	A	1	1	0	1	0	2	2
	B	2	1	0	2	0	2	2
#	A	3	3	0	1	0	2	2
	B	3	3	0	0	0	2	2
Almeria	A	3	3	3	2	0	2	2
	B	3	3	2	1	0	3	2

6.2. *Tomato chlorosis virus* (ToCV) and *Tomato infectious chlorosis virus* (TICV)

The Crinivirus genus includes another group of whitefly-transmitted viruses that are, however, less important than viruses inducing TYLCD. *Tomato chlorosis virus* (ToCV) and *Tomato infectious chlorosis virus* (TICV) belong to this group. While ToCV is transmitted by *B. tabaci* and *T. vaporariorum*, TICV is transmitted only by *T. vaporariorum*. Symptoms of TICV and ToCV in tomato are very similar and include interveinal yellowing, necrotic flecking, rolling, and thickening in older leaves, while the upper leaf appears normal. Yield reductions occur primarily due to the loss of photosynthetic area. Although no obvious fruit symptoms occur, production is reduced by decreased size and number of fruit.

No strict correlation between virus importance and insect vector prevalence has been observed for ToCV and TICV (Table 4). As expected, ToCV is present in the sites of Roussillon and Almeria where *B. tabaci* is an important problem, but unexpectedly it is not present in Catalonia#, where *B. tabaci* is an important problem as well. The semi-persistence of ToCV in its vector could explain the lack of correlation. Since ToCV is retained only for a few days after acquisition by its vector, it is less easily transmitted into a new environment than viruses causing TYLCD, which are retained for life by *B. tabaci* (persistent transmission). Figure 6 shows the geographical distribution of ToCV in Europe and neighbouring countries.

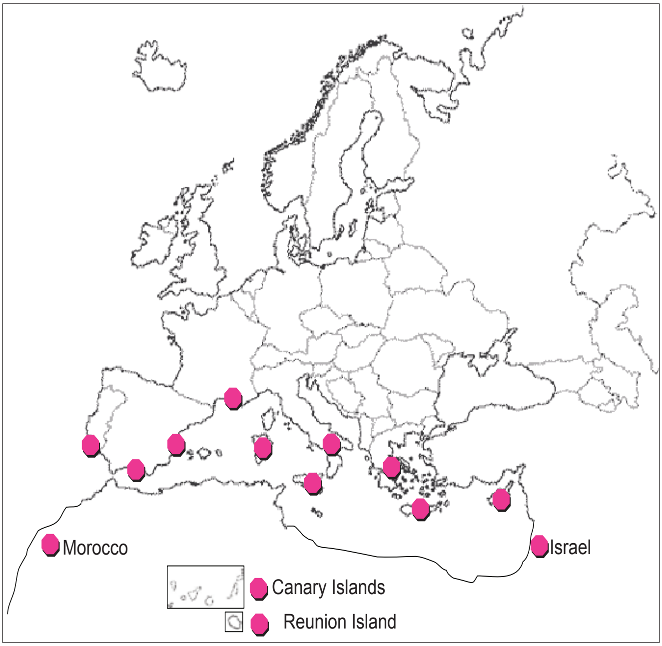


Figure 6. Distribution map of ToCV (●) in EU countries and the Mediterranean Basin (OEPP 2006; Segev et al., 2004; Delatte et al., 2006; Papayiannis et al., 2006).

On the other hand, TICV is absent in all surveyed sites, which is consistent with its relatively limited distribution (Dalmon 2007, and reference therein), unlike ToCV. The different geographical distribution between these two criniviruses is apparently because ToCV can be carried by both whitefly species but TICV only by *T. vaporariorum.* The prevalence of *T. vaporariorum* decreases with the increase of temperatures in summer, while the prevalence of *B. tabaci* increases simultaneously with the temperature. Consequently, the period of potentially efficient transmission for TICV is reduced. Finally, difficulties with the identification of the symptoms caused by ToCV and TICV, as opposed to those of nutritional deficiency or ageing of the plants, can result in some delays between the outbreak of criniviruses in a new area and their subsequent detection.

6.3. Other viruses transmitted by insects

Among the insect-transmitted viruses, *Tomato spotted wilt virus* (TSWV) has been identified as important or very important in crops of France and Spain. As with TYLCV, correlation has also been detected between TSWV and its thrips vector, *Frankliniella occidentalis* (Table 4). Thus, in Germany where *F. occidentalis* is reported as not very important, TSWV is also non-problematic, while in the other sites vector as well as virus are reported as important or very important.

7. Sampling techniques for decision making

According to results from the first questionnaire, 19 of the surveyed geographical areas base their decision making on *B. tabaci* control on thresholds, while the other 6 areas only consider calendar treatments. Frequently, whitefly population sampling is performed by counts of adults of both whitefly species on plants or yellow traps.

Data from the second questionnaire show that sampling techniques do not depend on control strategies (Chemical, IPM-Insecticide, IPM-BC and Organic) or growing cycle (long or short). Whitefly populations (adults and/or old nymphs) are usually sampled weekly. When the risk of whitefly occurrence is low or its impact presumably less important, samplings are operated fortnightly. There is no common sampling procedure or common sampling unit. Each country or region is using its own procedure for population follow-up and decision making, which is generally based upon whitefly densities. Thus 4 sampling techniques associated with the 4 different geographical locations have been reported. In Almeria, observations consist of 3 leaves (up, middle and bottom) per plant from 20 plants per hectare. In Catalonia, 3 leaves on 20 to 30 plants are monitored in the greenhouse perimeter when plants are young and 7 leaves on 14 plants when plants are fully grown. In Roussillon, at each sampling operation, leaves of 15 entire plants per hectare are observed. At the beginning of the crop, 50 instead of 15 plants are sampled. In Germany, 20 to 100 entire plants per hectare are monitored. In Almeria, Roussillon and Germany, advisors complement their plant sampling with yellow sticky traps (a mean of 15 traps/ha). For population monitoring and control, whitefly species are always identified. Decisions are made on both calendar and threshold basis, although calendar decisions essentially relate to chemical control strategies.

8. Whitefly control strategies

According to data collected, insecticidal whitefly control is used in all the surveyed countries. However, biological control is increasingly being used in the majority of geographical areas, especially in greenhouse crops. Other control tools such as nets, resistant cultivars, and cultural methods are also applied but to a lesser extent.

Effective whitefly control within protected environments is principally achieved through IPM strategies. In terms of hectarage, IPM-Insecticide is used as a control strategy in 70% of the surveyed area, IPM-biological Control (BC) in 25%, and Chemical control only in 5%. Organic production is the least extensive production strategy in all the surveyed regions. Among all, IPM-BC is the most common strategy applied in Germany (cycles A and B), Roussillon, and some areas of Catalonia, whereas IPM-Insecticide is the most common strategy used in Almeria and Catalonia # (Table 5). In Catalonia#, IPM based on insecticide use accounts for 80% of the surveyed surface, whereas in Catalonia it represents only 15-30%. Although these two areas are very close, less than 50 km apart, and have similar climate conditions, they present different crop cycle duration. Populations of *B. tabaci* and TYLCD incidence are higher in Catalonia#, which can be explained, at least partially, by a higher use of insecticides, since higher populations of *B. tabaci* were recorded from crops where whitefly control relied only on insecticides compared to crops where IPM-BC was used (Arnó, 2005).

Table 5. Pest control strategies used for different growing cycles in the surveyed regions. See figure 2 for cycle description

Area	Cycle	Total surface (ha)	% Chemical	% IPM-Insecticides	% IPM-BC	% Organic
Germany	A	3	-	-	90,5	9,5
	C	17	6	18	70	6
Roussillon	A	20	-	18	72	10
	B	35	-	100	-	-
	C	50	-	20	80	-
Catalonia	A	31	11	19	69	1
	B	18	7	8	69	16
#	A	17	30	50	20	-
	B	15	30	50	20	-
Almeria	A	6700	3	78	19	-
	B	3300	7	58	35	-

8.1. Insecticides

Data collected reveals that, unlike other pest species of tomatoes, the ranked importance of *B. tabaci* within each of the four surveyed regions closely correlates with the levels of insecticide use (Figure 7). This shows *B. tabaci* to be one of the principal insect pests driving insecticide use, primarily due to the threat of TYLCD and the resulting low tolerance thresholds that it imposes. However, even in areas where *B. tabaci* is not of concern, chemical control of whiteflies remains an important component.

When the average number of insecticide applications per month is analysed, it is apparent that a higher number of applications is used in those areas with high pressure of *B. tabaci* and TYLCD. As expected, the number of insecticide applications per month is higher in IPM-Insecticide than in IPM-BC strategies in all areas except Germany (low whitefly) and Catalonia (same advisors were responsible for recommendations of both strategies). Not only insecticide applications but also active ingredients (a.i.) are saved with the use of IPM strategies: IPM-Insecticide uses 18% less a.i. per application than the chemical strategy and 17% more a.i. per application than IPM-BC (Table 6). Thus, IPM-BC is the recommended control strategy for a more sustainable tomato production.

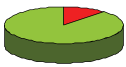
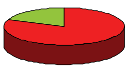
Control strategies **Insecticides** **Other**	**Average rank of *Bemisia* importance**
Germany 	**1.0**
Roussillon 	**2.2**
Catalonia 	**2.3**
Almeria 	**3.0**

Figure 7. Chemical reliance of control strategies employed within the four surveyed tomato-producing regions of Europe. Numbers refer to the average rank (0-3) of *Bemisia tabaci* pest importance (see Table 6).

Table 6. Insecticide applications per month for each crop cycle, pest control strategy, and area: < 1 application/month, from 1 to 2 applications/month, and > 2 applications/month. See figure 2 for cycle description

Area	Cycle	*B.tabaci*	TYLCD	Insecticide applications/month		
				IPM-BC	IPM-Insec.	Chem.
Germany	A	1	0	<1		
	C	1	0	<1	<1	<1
Roussillon	A	1	1	<1	<1	
	B	3	3		>2	
	C	3	3	<1	>2	
Catalonia	A	1	1	<1	<1	<1
	B	2	1	<1	<1	<1
#	A	3	3	<1	<1	<1
	B	3	3	<1	<1	1 - 2
Almeria	A	3	3	1 - 2	>2	>2
	B	3	3	1 - 2	>2	>2

Average number a.i. /application	1.5	1.8	2.2

Insecticide resistance has been reported for both whiteflies, especially for *B. tabaci*, to all the pesticide compounds used: organophosphate, pyrethroid, carbamate and neonicotinoid chemistries, and the specific insect growth regulators, pymetrozine and pyridaben.

Insecticide resistance is a primary constraint, not only to effective chemical strategies application but also and more importantly as the chemical backup that supports the performance and sustainability of IPM. With a requirement for IPM compatibility, insecticidal control of whiteflies has increasingly centred on a limited number of selective compounds, many of which are compromised by resistance development. Consequently, some growers that are using control strategies based on insecticides are reverting to broader-spectrum compounds with greater toxicity to both biocontrol agents and insect pollinators. For *B. tabaci*, the lack of genetic introgression between biotypes B and Q can result in different insecticide resistance profiles. This can lead to a competitive advantage when particular insecticides are used, which potentially has a dramatic influence on biotype ratios and distribution patterns.

8.2. Biological control

Natural enemies used for biological control of whiteflies in the countries surveyed as part of the first questionnaire are: *Eretmocerus mundus* in 9 countries, *Typhlodromips (=Amblyseius) swirskii* and *Macrolophus caliginosus* in 7 countries, *Eretmocerus eremicus* and *Nesidiocoris tenuis* in 4 countries, *Encarsia formosa* in 3 countries, and *Dicyphus hesperus* in 2 countries. Figure 8 shows the use of these natural enemies in the different locations in tomato, eggplants, pepper, cucurbits, and ornamentals. As it can be observed, more non-European species are used in northern locations than in the Mediterranean countries.

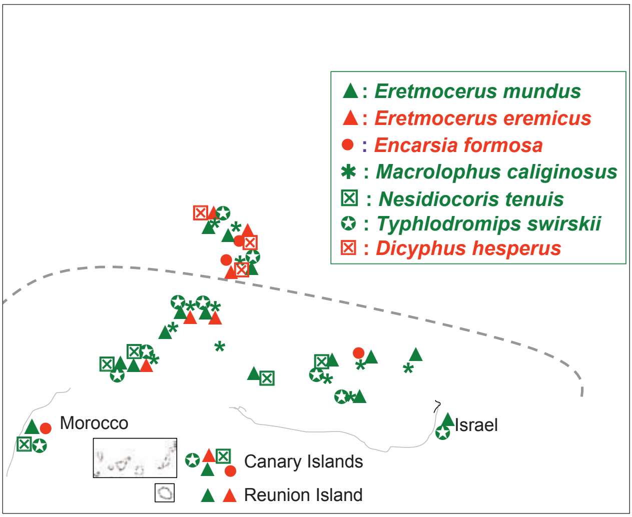


Figure 8. Natural enemies used in biological control of whiteflies in the different countries. Symbols in red are used for non-European native beneficials.

Data from the second questionnaire reveals that IPM-BC is applied in all 4 tomato-growing areas surveyed, being the largest hectarage (> 2000 ha) in Almeria. Biological control of whiteflies is mainly based on inoculative releases of the parasitoids *E. mundus* and *E. formosa* and/or the polyphagous predators *M. caliginosus* and *N. tenuis*. Only in Catalonia, a program based on the conservation of native populations of *M. caliginosus* is also used. Rates of natural enemies are very variable, depending on the area and the crop cycle. Releases of parasitoids are based on adult whitefly thresholds (1-2 whitefly adult/plant), whereas in the case of predators releases are often calendar based. This is probably due to both predator availability and their slow installation on the crop, forcing the release of predators from the outset. In Catalonia, *M. caliginosus* release rates are configured according to natural populations of the predator at the start of the crop. However, decisions relating to beneficial species and rates usually rely also on the experience of advisors. Data on the different beneficials used and the release rates in the different areas and crop cycles are summarized in table 7.

Among the predators, *M. caliginosus* is widely released in Germany, Roussillon and Catalonia, whereas *N. tenuis* is only introduced in the tomato greenhouses in Almeria. Release rates of *M. caliginosus* range from 0.5 to 4 adults/m^2, while *N. tenuis* is released at a rate of 1 adult/m^2. Since *N. tenuis* can cause damage to tomato plants when prey is scarce, lower release rates are probably recommended.

The parasitoid species used for whitefly control are tightly correlated to the whitefly species present in the different crop cycles and growing areas. *Eretmocerus mundus* only parasites *B. tabaci* and is widely used in the Mediterranean basin during the tomato-growing cycles when this whitefly is the predominant species. *Encarsia formosa* is used in Germany and Roussillon, principally for *T. vaporariorum* control. Release rates of both parasitoid species are very variable: from 3 to 10 individuals/m^2 in the case of *E. mundus* and from 4 to 55 individuals/m^2 in the case of *E. formosa.* It is noteworthy that in Roussillon *E. eremicus* is released when no *E. mundus* is available.

Photo 7. *Macrolophus caliginosus*. © Photo from IRTA Entomology.

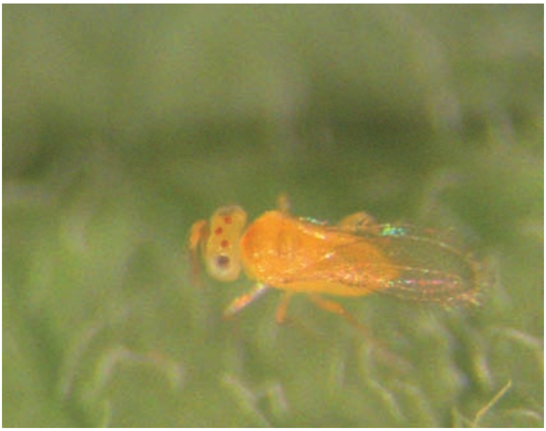


Photo 8. *Eretmocerus mundus.* © Photo from IRTA Entomology.

Table 7. Natural enemies and release rates (individuals/m^2) used in the different European areas surveyed. See figure 2 for cycle description

Area	Cycle	*Macrolophus caliginosus*	*Nesidiocoris tenuis*	*Eretmocerus mundus*	*Encarsia formosa*
Germany	A	1.5	-	-	4-8
	C	0.5-2.5	-	-	7.5-9
Roussillon	A	4	-	-	25-55
	C	3	-	10	10
Catalonia	A	2-3	-	3-9	-
	B	2	-	3-9	-
#	A	1	-	-	-
	B	1	-	3-6	-
Almeria	A	-	0.75	10	-
	B	-	1	10	-

Biological control is used mainly within the framework of IPM programs as a method to control some pests. In those programs, selective pesticides are applied for other pests lacking biological solutions or when biological control fails to maintain the target pest under the economic threshold. Natural enemies are also used in organic production, although the hectarage of tomatoes under this production system is very limited.

8.3. Other control tools to control whitefly

Important components of IPM strategies are physical control tactics and virus plant resistance. The use of nets in vents and double-door entry systems to reduce the movement of *B. tabaci* into greenhouses and the use of tomato varieties tolerant to TYLCD are applied most extensively in areas with high pest pressure and TYLCD incidence, namely Almeria, Catalonia# and Roussillon. Yellow sticky traps are also used in some areas as a whitefly control method. Their use is not so much correlated with *B. tabaci* pressure but with the tomato-growing area.

Genes that confer tolerance to TYLCV have been identified in various wild relatives of tomato and tolerant tomato lines developed by breeding. Most commercial cultivars tolerant to TYLCD have the *Ty-1* gene. The best available cultivars and breeding lines show tolerance rather than resistance to the virus. Moreover, as the yield of these tolerant cultivars may be affected by early infections, they need additional protection from viruliferous insects such as insect control strategies or nets during the first months after planting.

Since so many different viruses are transmitted by whiteflies, it becomes a more attractive strategy to focus on plant-based resistance to the vector rather than to the virus. At present, varieties fully resistant to whiteflies have not been described. In tomato, resistance towards *B. tabaci* is found in wild relatives of the cultivated tomato (Muigai et al., 2003). Whitefly plant defence is at least partly based on the glandular trichomes. Tomatoes contain glandular and non-glandular trichomes. Both types can hinder insect in their movement and, thus, may have an effect on their susceptibility towards whiteflies. Several groups have studied the effect of trichome density and found a small but significant negative correlation between the densities of type IV trichomes and whiteflies. However, trichome exudates have a much stronger effect. Secondary metabolites with insecticidal activity in trichome exudates are present in wild relatives of the cultivated tomato and are responsible for the observed insect resistance. However, until now breeding efforts have been without success. This is probably due to the parallel existence of several resistance-conferring metabolites that are determined by a number of independent genes, hampering their combined transfer to a single variety of cultivated tomato.

The thrips-vectored TSWV has also been reported as an important disease in several tomato-growing areas. Tomato cultivars resistant to TSWV have been obtained through the use of the single viral resistance gene Sw-5. The use of TSWV resistant cultivars in the different areas and crop cycles is not correlated with the incidence of the virus, nor the vector.

9. Recommendations to manage *B. tabaci* and TYLCD in tomato crops

In a sustainable agriculture scenario, IPM-BC is the most suitable control strategy for improving *B.tabaci* and TYLCD control on tomato greenhouses. Potential limitations for a wider adoption of IPM-BC programs in tomato crops have been identified (tables 8.1 and 8.2).

Table 8.1. Method-related limitations for IPM-BC strategy implementation in the different scenarios surveyed with different *B. tabaci* pressure and whitefly-vectored virus incidence

METHOD LIMITATIONS	Almeria	Catalonia#	Catalonia	Roussillon	Germany
Lack of biological solution for some pests	4	4	4	2	1
Low acceptance of the method by the farmer	3	3	3	2	1
Low pest injury threshold	4	3	1	2	1
Lack of trained advisors	2	4	1	1	2
Lack of experience	2	4	1	1	1
Protocols available do not work (climate)	1	3	2	1	1
No availability of commercial natural enemies	1	1	2	1	1

Table 8.2. Cost-related limitations for IPM-BC strategy implementation in the different scenarios surveyed with different *B. tabaci* pressure and whitefly-vectored virus incidence

COST LIMITATIONS	Almeria	Catalonia#	Catalonia	Roussillon	Germany
Natural enemies are expensive	1	3	3	2	3
Increase costs due to the need for technical advice	4	1	1	1	3

The category "lack of a biological solution for some pests" is the most extended limitation, especially in Spain. This area is being increasingly affected by a harmful mite, *A. lycopersici,* which has neither an efficient biological control agent nor an efficient authorized acaricide. In addition, "cost of natural enemies" is considered high in all surveyed areas. The second most important limitation is "low acceptance of the method on behalf of the farmer", especially around the Mediterranean basin, where the difficulty to apply IPM in small surface areas might explain farmer's reluctance, according to some advisors opinion. Efficient training of the farmers and advisors will improve their knowledge of IPM-BC strategies and, consequently, increase the confidence in this control method on behalf of the end-user. "Increase of costs associated with technical advice" is an important constraint to the implementation of IPM-BC in Almeria and Germany. On the other hand, in Roussillon and Almeria "low pest injury thresholds" make farmers reticent to initiate an IPM control program, which is probably connected to the high incidence of TYLCD in theses areas.

10. Future research needed to apply IPM programs

A wider adoption of IPM programs is needed to promote a more rationalised and reduced pesticide input. Efficient IPM control strategies are based on a cohesive knowledge of the ecology, behaviour, and genetics of pest organisms. As a need to address the current knowledge gaps in those areas, we propose research in the following domains:

(i) **On whitefly-transmitted viruses**. The risk associated to new geminiviruses and their potential recombination requires ongoing continuous/periodical support. Four geminivirus species have been identified in Europe in addition to 50 more distinct geminiviruses detected around the world and identified all in tomato. Some non-European tomato geminiviruses could be introduced into Europe and recombine with European viruses to produce new species. To assess such a risk, the impact of recombination on virulence and fitness should be studied. Preliminary results indicate that most recombinants are infectious, but how frequently a recombinant genome is more virulent and fitter than its parental viruses is still unknown. Moreover, we ignore if cultivars that were bred for resistance to TYLCV are resistant to the other tomato geminiviruses (Lapidot and Friedmann, 2002).

(ii) On insecticide-resistance in whitefly populations and *B. tabaci* biotypes. Two specific knowledge gaps continue to limit a more effective, efficient, and selective chemical control of whiteflies. Both require ongoing continuous/periodical research.

ii.a. Resistance assessments. Levels of insecticide resistance are dynamic and can be either localized or widespread. Contemporary monitoring data are necessary to make appropriate and informed insecticide choices. The relevance of *B. tabaci* biotypes to insecticide resistance in Europe is unknown. If biotypes B and Q display different resistance status, as it has been the case for some years, control strategies can be more efficient if they are tailored to suit the biotype in question. Conversely, if little or no differential exists, as in some other global regions, biotype status will have minimal impact upon insecticide efficacy.

ii.b. Biotype assessments. Building on the previous point, biotype assessment may be an effective means of predicting the likely resistance expressed by local populations, and therefore it should be monitored accordingly. Updated knowledge on the status of European *B. tabaci* biotypes may give complementary information on *B. tabaci* invasiveness, whitefly infectivity of viral diseases, and several aspects of *B. tabaci* biology.

(iii) On host plant resistance to whiteflies and whitefly-transmitted viruses. Tomato has several closely related relatives that can be a source of resistance/tolerance traits towards whitefly populations and TYLCD. Some of those traits are currently being studied, but several aspects of the mechanisms involved are still poorly understood. Other traits and mechanisms should be investigated with the aim of improving resistance of commercial tomato varieties.

iii.a. Resistance mechanisms. Breeding programs designed to introduce resistance traits into cultivated tomato require the study of the resistance mechanisms in different wild relatives of tomato and the identification of the active compounds involved. Interactions between *B. tabaci* biotypes and the resistance mechanisms in the host plant need to be evaluated as well.

iii.b. Biochemistry and genetics of resistance. To understand host plant resistance, the underlying biosynthetic pathways for the active compounds have to be identified, and the genes involved need to be identified and tagged.

(iv) On the economic thresholds and sampling techniques for whitefly populations. One of the conclusions drawn from the questionnaires in the case study dealt with the various methods applied to whitefly population sampling. Sampling techniques are closely related to economic thresholds, and limitations complicate the efficient and selective application of control strategies. Two research priorities are proposed to alleviate these limitations:

iv.a. Sampling for decision making on whitefly control. Identification of the optimal sampling unit and the design of a sampling plan (size, frequency, and timing of sampling) would be advantageous to establish consistent protocols efficiently estimate whitefly populations.

iv.b. Economic thresholds for decision making. Economic thresholds *per se* are too static parameters to be considered as universal for making decisions on whitefly control. Economic thresholds as a function of whitefly population dynamics, in addition to insect density and damage relationships, would likely be more applicable to a range of situations.

(v) On whitefly natural enemies and biological control. One of the conclusions from the second questionnaire is that IPM-BC is the best control strategy to reduce pesticide residues on tomato crops. However, some important factors limit a wider uptake and highlight the need to increase research in the following fields:

v.a. Improvement of whitefly biological control based on natural enemies conservation. In Mediterranean areas natural enemies are abundant, and their conservation has demonstrated to efficiently control whitefly populations. Developing conservation tactics to enhance the natural enemies in tomato crops would lead to (a) reducing the natural enemies release rates that are currently being used and, consequently, the cost of IPM-BC programs, and (b) identifying new native, potential biological control agents.

v.b. Improvement of biological control of other key pest. Lack of effective natural enemies to control *Aculops lycopersici, Helicoverpa armigera, Frankliniella occidentalis*, and leaf miners is an important limitation for the implementation of IPM-BC, especially in the Mediterranean area, where the larger surface of tomato production is located. Developing biological control strategies to manage these pests is crucial to increase the use of IPM-BC programs and reduce insecticide use.

11. Glossary

Whitefly species and biotypes

Bemisia tabaci is considered a species complex with a number of recognized biotypes. *Bemisia tabaci* has been reported from all continents except Antarctica. Over 900 host plants have been recorded, and it reportedly transmits 111 virus species. It is believed that *B. tabaci* has been spread throughout the world through the transport of plant products infested with whiteflies. Once established, *B. tabaci* quickly spreads and, through its feeding habits and the transmission of several virus diseases, may cause destruction to crops around the world. This species has been classified among the 100 “world’s worst” invaders (Lowe et al., 2000).

Trialeurodes vaporariorum is essentially temperate and subtropical. Introduced accidentally into Western Europe, it now constitutes a major pest in protected crops and also transmits plant viruses.

Main virus species transmitted by whiteflies in present Europe

TYLCD, Tomato yellow leaf curl disease. The causing agents of this disease are a complex of virus species of the genus Begomovirus (family Geminiviridae). The most important species reported in Europe are:

> **TYLCV,** *Tomato yellow leaf curl virus* (Begomovirus). Insect vector: *B. tabaci.* Crops affected: *Capsicum annuum, Solanum lycopersicum,* and *Phaseolus vulgaris.* Impact: Severe yield reduction and heavy economic losses, mainly in tomato.
>
> **TYLCSV,** *Tomato yellow leaf curl Sardinia virus* (Begomovirus). Insect vector: *B. tabaci*. Crop affected: *S. lycopersicum.* Impact: Severe yield reduction and heavy economic losses.

ToCV, *Tomato chlorosis virus* (Crinivirus). Insect vector: *B. tabaci* and *T. vaporariorum*. Crop affected: *S. lycopersicum*. Impact: Yield reduction due to loss of photosynthetic area, reduced fruit growth, and delayed ripening.

TICV, *Tomato infectious chlorosis virus* (Crinivirus). Insect vector: *Trialeurodes vaporariorum.* Crop affected: *S. lycopersicum*. Impact: Yield reduction due to loss of photosynthetic area, reduced fruit growth, and delayed ripening.

Other virus species transmitted by relevant insects in tomato crops

TSWV, *Tomato spotted wilt virus.* Insect vector: *F. occidentalis*. Crops affected: many species including *S. lycopersicum* and *C. annuum.*

Pest control strategies

IPM (Integrated Pest Management) is an effective and environmentally sensitive approach to pest management that relies on a combination of common-sense practices. The IPM programs use current, comprehensive information on the life cycles of pests and their interaction with the environment. This information, in combination with available pest control methods, is used to manage pest damage by the most economical means whilst minimising associated hazards to people, property, and the environment.

Pesticide residues

MRL (maximum residue level). All foodstuffs intended for human or animal consumption in the European Union (EU) are subject to a MRL of pesticides in their composition in order to protect animal and human health.

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