Bedding plant production and the challenge of fungal diseases

Vladimiro Guarnaccia[1,2], Francesca Peduto Hand[3], Angelo Garibaldi[1], M. Lodovica Gullino[1,2*]

[1]Centre for Innovation in the Agro-Environmental Sector, AGROINNOVA, University of Torino, Largo Braccini 2, 10095 Grugliasco (TO), Italy.
[2]Department of Agricultural, Forest and Food Sciences (DISAFA), University of Torino, Largo Braccini 2, 10095 Grugliasco (TO), Italy.
[3]Department of Plant Pathology, The Ohio State University, Columbus, OH 43220, USA.
*Corresponding author: M. L. Gullino; E-mail: marialodovica.gullino@unito.it

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ABSTRACT

Bedding plants are a major group of ornamentals produced in greenhouses or nurseries worldwide and planted outdoors. Their economic importance has increased continuously in the last four decades in both the United States and the European Union. These plants are subject to many diseases that can negatively impact their production and cultivation. The initial steps of production strongly influence the health status of these plants and, consequently, their aesthetic appeal, which is a strong requisite for consumers. Seeds, cuttings, other forms of propagative material, along with production systems and growing media can influence the phytosanitary status of the final product. In this paper, case studies of soil-borne and foliar diseases are presented together with preventive measures to achieve innovative disease management strategies. Quarantine restrictions and eradication measures are also discussed, in consideration of the high likelihood for ornamental plants to be long-distance vectors of new pathogens and pests.

BEDDING PLANTS, PRODUCTION AND MARKET

Bedding plants are fast growing annuals or herbaceous perennials (Fig. 1) used outdoors in flowerbeds or planters, in gardens, on balconies, or around buildings. The bedding plant industry is mainly local, with very limited export of the products but including massive distribution direct to consumers by large chain stores. The choice of plants often reflects trends and consumers' taste at the local level.

The total value of bedding and garden plants in the United States was $2.16 billion in 2018, which was up 7% compared to 2015, and represented 47% of the total wholesale value of the floriculture crops sector (USDA 2019). In Europe, the production of bedding plants encompasses a very significant part of the of the ornamental plants sector that registered a wholesale value of €2.2 billion in 2019, with The Netherlands accounting for 30% of the total production followed by Italy and Germany, each accounting for 13% (European Commission 2019).

Bedding plant cultivation in temperate climates, such as those of both the United States and Europe, starts under greenhouse conditions in late winter–early spring. Plants are grown in a variety of formats: in flats, pots, or hanging baskets. Sometimes different plant species are grown and sold as mixed items in the same container, for use as hanging baskets or patio containers. A very wide variety of plant species is often grown within the same greenhouse range. Plants are sold in garden centers, big box stores, farm stands, or street markets and planted at the beginning of the growing season, as soon as the risk of frost has passed (Daughtrey and Buitenhuis, 2020). Most genera and species are subject to a number of diseases, whose severity varies according to the species and cultivar as well as the characteristics of the production process of the industry. The production cycle is generally shorter in comparison to other floriculture crops, making disease management less complex, as plant pathogens have less time to cause severe losses during the production time. The quality of the cultivation practices strongly influences the health status of the finished plant.

RECENT CHANGES IN PRODUCTION

Genera and species grown

Many genera and species are grown as bedding plants, with a strong influence of local trends and continuous changes due to changes in customers' preferences. Besides the most familiar and popular annuals, herbaceous perennial species are increasingly grown, leading to a very high total number of cultivated species. The species shown in Figure 1 are some of those commonly produced in the United States and Europe; nevertheless, different countries are specialized in production of certain species, such as impatiens and begonia in the United States, bulb species (e.g. tulip, lily, hyacinth, gladiolus, narcissus, etc.) in the Netherlands, and cyclamen and *Asteraceae* (e.g. coneflower, chrysanthemum, etc.) in Northern Italy. New cultivars as well as new species are continuously introduced each year, making not only the market but also the phytosanitary situation quite variable and dynamic.

Production practices, including cultural methods, substrates, inputs in relation to plant health

Since the industry is localized and offers an abundant variety of plant choices, it is not uncommon to find hundreds of species and cultivars originating from different specialist propagators grown in the same greenhouse. Propagules may be sourced from many parts of the world, but then distributed locally after they reach transplant size. The practice of using seeds or unrooted cuttings from global sources strongly increases the risk of introduction of pathogens that may quickly spread from infected to healthy plants. Production practices, which are very fragmented and strongly related to the size of the facility, influence the health status of the final product.

Propagative material

Bedding plants can be started from seeds or cuttings and both of them can be a source of pathogens. In recent years, well-rooted, transplant-ready seedlings or cuttings in plug trays replaced the seeding step for growers of many crops such as begonia and dianthus. Global distribution of unrooted cuttings to rooting stations or direct to growers who finish the crops has sped up the process of introducing new lines. For example, in the United States, 10% of petunias are propagated from cuttings (Daughtrey and Buitenhuis 2020). Vegetative propagation material is shipped to growers directly as unrooted cuttings or it is first rooted in rooting stations and then sold to growers as rooted cuttings. Such early steps in plant production are very critical, and the health status of the final crop strongly depends upon the quality of the measures adopted at the propagation, rooting station or plug production steps, before the young plant (as seedling or rooted cutting) reaches the finisher (Daughtrey and Buitenhuis 2020).

Cultivation systems and growing media

Soilless culture has been gaining popularity in the ornamental industry (Gullino and Garibaldi 2007), allowing in most cases to start a production cycle completely free of pathogens. Although such a growing system is ultimately intended to reduce production costs and maximize profits, precise environment and nutrition controls that push plants to new limits of growth and productivity can generate chronic stress conditions, which are difficult to measure, but are apparently conducive to diseases caused by pathogens such as *Penicillium* spp. or *Pythium* spp. (Garibaldi and Gullino 2010).

A variety of growing media has been developed which provides growers with very broad options that can be tailored to the specific crop grown and the type of cultivation adopted. During the past two decades, much attention has been devoted to the selection of media that not only support good growth, but also suppress important pathogens (Pugliese et al. 2015).

CASE STUDIES

This section aims to review the most important groups of pathogens causing severe diseases on bedding plants, with special emphasis on those most recently reported (Fig. 2).

Fusarium wilts

The genus *Fusarium*, which was recently separated into several *Fusarium*-like genera, (i.e., *Bisifusarium* [*Fusarium dimerum* species complex (SC)] or *Neocosmospora* [*Fusarium solani* SC]), includes highly important plant pathogens, affecting several hosts (Guarnaccia et al. 2019; Lombard et al. 2015; O’Donnell et al. 2010). *Fusarium* species are well-known causal agents of diseases of ornamental plants, including bedding plants and other herbaceous and woody ornamentals (Guarnaccia et al. 2019a; Gullino et al. 2015), occurring at all plant production stages.

Fusarium wilts, caused by several *formae speciales* of *F. oxysporum* (Booth, 1984) or novel species members of the *F. oxysporum* species complex recently described (Lombard et al. 2019), can generate economic losses in commercial greenhouses where a wide range of ornamental species are cultivated (Elmer 2008; Wang and Jeffers 2002).

Bedding ornamentals that are susceptible to Fusarium wilts include a number of species in the genera *Aster*, *Begonia*, *Dianthus*, *Cyclamen*, *Eustoma*, and *Gerbera* (Gullino et al. 2015; Minuto et al. 2007; Sinclair and Lyon 2005). Woody ornamentals such as *Ailanthus*, *Albizia*, *Bougainvillea* spp. can also be affected (Guarnaccia et al. 2019a; Sinclair and Lyon 2005).

Fusarium oxysporum f. sp. *chrysanthemi* causes wilt of chrysanthemum (Armstrong et al. 1970; Jackson and McFadden 1961). Similarly, wilts caused by the same f. sp. were reported on three hosts in the Asteraceae family (Fig. 3): gerbera daisy (*Gerbera jamesonii*), Paris daisy (*Argyranthemum frutescens*), and African daisy (*Osteospermum* sp.) (Garibaldi and Gullino 2012b; Garibaldi et al. 2004; Li et al. 2010; Minuto et al. 2007). A subsequent study revealed the presence of three physiological races in *F. oxysporum* f. sp. *chrysanthemi* causing different pathogenic reactions on various cultivars of the same host species (Troisi et al. 2013). Race 1 of this f. sp. has also been found associated with chrysanthemum in both the United States (Horst and Nelson 1997) and Italy (Garibaldi and Gullino 2012b). Moreover, *F. oxysporum* f. sp. *chrysanthemi* has been reported as pathogenic on orange coneflower (*Rudbeckia fulgida*), which emphasizes its expanded host range (Table 1) (Garibaldi et al. 2017a;

Matić et al. 2018). Gerbera and argyranthemum plants cultivated in Italy and Brazil have been found infected by *F. oxysporum* f. sp. *tracheiphilum* (Garibaldi and Gullino 2012b; Troisi et al. 2010a).

Fusarium wilt caused by *Fusarium oxysporum* f. sp. *cyclaminis* commonly occurs on cyclamen (*Cyclamen*), where it causes major losses. This risk has led several growers in the United States and Europe to abandon this crop (Fig. 4) (Elmer and Daughtrey 2012; Tompkins and Snyder 1972). No races have been identified. However, three clones have been identified based on vegetative compatibility groups and RFLP analysis (Woudt et al. 1995).

The dianthus industry in Italy, France, and Spain suffered a strong reduction in acreage cultivated due to *F. oxysporum* f. sp. *dianthi* and *F. redolens* f. sp. *dianthi* (Garibaldi and Gullino 2012a). Moreover, *F. oxysporum* f. sp. *dianthi* has been reported on plants cultivated in Colombia and the United States (Chase et al. 2018; Garibaldi et al. 2011a).

Lisianthus (*Eustoma grandiflorum*) is also affected by *F. oxysporum* f. sp. *eustomae* (Li et al. 2010) and the presence of three pathogen groups was demonstrated based on genetic diversity and vegetative compatibility (Bertoldo et al. 2015). *F. oxysporum* f. sp. *eustomae* is the typical example of a *forma specialis* restricted to only one host species, lisianthus. However, other *formae speciales* such as *F. oxysporum* f. sp. *chrysanthemi* have a broader host range (chrysanthemum and coneflower). Similarly, one host plant can be susceptible to multiple *formae speciales*, as occurs for *Gerbera jamesonii,* which can show typical wilt symptoms caused by *Fusarium oxysporum* f.

sp. *chrysanthemi* and *F. oxysporum* f. sp. *tracheiphilum* (Garibaldi et al. 2004, 2008; Minuto et al. 2007; Troisi et al. 2013). *Fusarium oxysporum* causing wilting on *Lewisia cotyledon* and *F. oxysporum* f.sp. *ranunculi* infecting *Ranunculus* spp. have been reported in Italy (Garibaldi and Gullino 1985).

Oomycetes

Several species of oomycetes in the genera *Phytophthora* and *Pythium* are well known causes of root and foliar diseases on a wide range of ornamental plants (Aiello et al. 2018; Erwin and Ribeiro 1996; Ferguson and Jeffers 1999; Jung et al. 2016; Prigigallo et al. 2015; Schwingle et al. 2007; Werres et al. 2001), and cause billions of dollars in losses to crops worldwide (Kamoun et al. 2015), including ornamentals.

Oomycete diseases are common in ornamental greenhouses where warm temperatures, high humidity, and densely grown plants present favorable conditions for pathogen growth and sporulation (Donahoo and Lamour 2008). Moreover, irrigation sources and practices play a key role in pathogen spread (Hong and Moorman 2005; Yamak et al. 2002).

Surveys of nurseries and greenhouses for species of *Phytophthora* have been conducted in several states in the United States in the last 15 years (Donahoo and Lamour 2008; Hong et al. 2006; Hu et al. 2008; Hwang and Benson 2005; Olson and Benson 2011; Olson et al. 2013; Schwingle et al. 2007; Warfield et al. 2008; Yakabe et al. 2009).

P. nicotianae infects approximately 260 genera, including many herbaceous and woody plants, and is present in nurseries and greenhouses worldwide (Cline et al. 2008). This species is the most commonly encountered in bedding plants in the United States, where it causes extensive losses both in production and in the landscape (Olson et al. 2013). The pathogen causes root and crown rot on *Gerbera jamesonii* and pansy, as well as aerial blight on annual vinca (*Catharanthus roseus*), calibrachoa (*Calibrachoa* x *hybrida*), and most recently on lobelia (*Lobelia erinus)* (Lin et al. 2018). The symptoms caused by *P. nicotianae* develop at temperatures higher than 28°C, but oomycete colonization occurs at lower temperatures (Chase et al. 2018).

Phytophthora tropicalis is a relevant pathogen on numerous ornamental bedding plants, such as annual vinca (*Catharanthus roseus*) (Hao et al. 2010), cyclamen (*Cyclamen persicum*) (Gerlach and Schubert 2001), gloxinia (*Sinningia speciosa*), verbena (*Verbena × hybrida*) (Olson and Benson 2011), begonia (*Begonia* sp.), gerbera (*Gerbera jamesonii*), lupine (*Lupinus albus*), and dusty miller (*Senecio bicolor*) (Hong et al. 2008).

In gerbera, *Phytophthora cryptogea* is responsible for severe root rot resulting in stunting, wilting and death of plants (Garibaldi et al. 2003a). However, gerbera is grown in soilless mixes in both the United States and Europe (Tognoni and Incrocci 2003). Notably, diseases observed in hydroponic production have not developed when this species is grown in peat-based mixes. *Phytophthora cryptogea* is responsible for severe root rot resulting in stunting, wilting and death of plants (Garibaldi et al. 2003a). Beyond gerbera, *P. cryptogea* is reported worldwide as causing root and crown rot on a number of ornamental species, including *Begonia* spp., *Chrysanthemum morifolium*, petunia, *Salvia officinalis*, and *Verbena hybrida* (Chase et al. 2018; Garibaldi et al. 2015a). *Phytophthora drechsleri* is another *Phytophthora* species causing crown rot on bedding plants such as *Calibrachoa* spp., *Celosia argentea*, *Gerbera jamesonii*, and *Helichrysum bracteatum*. Recently, the newly described species *Phytophthora chrysanthemi* was reported on chrysanthemum in the United States (Lin et al. 2017), Europe (Tomic and Ivic, 2015) and Japan (Naher et al. 2011).

The genera *Pythium* and *Globisporangium* are often associated with damping-off and crown and root rot diseases during propagation, killing seedlings and cuttings (Daughtrey and Benson 2005; Garzón et al. 2011; Moorman et al. 2002). Primary inoculum of *Pythium* and *Globisporangium* spp. is commonly present in the soil and usually is introduced into greenhouses on contaminated containers. Moreover, seeds of bedding plants can be colonized by these oomycetes and contribute to inoculum transmission (Faust et al. 2017). *Pythium aphanidermatum*, *Globisporangium irregulare* (former *P. irregulare*) and *G. ultimum* (former *P. ultimum*) are the most common pathogens in the "Pythium root rot" group causing diseases of ornamental plants (Chase et al. 2018; Garibaldi et al. 2009a; Guarnaccia et al. 2015). Among the bedding plants most commonly affected by these oomycetes are *Pelargonium* spp., *Catharanthus roseus* (annual vinca) and *Impatiens* spp. In addition to root rot, affected plants may show stunting, yellowing or wilting of the foliage; occasionally, stem or crown rot or canker may occur in absence of root rot (Chase et al. 2018). When conditions are wet and humid, rot from the roots can proceed up to the basal leaves where presence of white hyphae can be observed (Moorman et al. 2002).

Downy mildews are also major threats: *Basidiophora*, *Hyaloperonospora*, *Peronospora,* and *Plasmopara* are the most common oomycete genera causing downy mildew in bedding plants. Patches of chlorosis and necrosis are typical symptoms produced on the upper leaf surface, whereas prolific white sporulation can be observed on the leaf underside. *Coleus*, *Impatiens*, *Matthiola* and *Viola* spp. are affected by *Peronospora belbahrii*, *Plasmopara obducens*, *Peronospora parasitica,* and *Hyaloperonospora parasitica*, respectively (Daughtrey et al. 2006; Koike 2000; Palmateer et al. 2008; Rivera et al. 2016). Other common hosts in the Unites States include salvia (*Peronospora lamii;* Choi et al. 2009), snapdragon (*P. antirrhini;* Byrne et al. 2005) and verbena (*P. verbenae*; Braun et al. 2009). *Peronospora digitalis* and *P. arthurii* caused outbreaks on *Digitalis purpurea* (Fig. 5) and *Oenothera biennis* in the United States, several European countries, and New Zealand (Belbahri et al. 2005; Garibaldi et al. 2013a, 2018a).

Rhizoctonia solani

Diseases of ornamental plants caused by *Rhizoctonia* spp. commonly occur in greenhouse, nursery and landscape (Aiello et al. 2017; Daughtrey and Benson 2005). *Rhizoctonia solani* (teleomorph *Thanatephorus cucumeris*) is a necrotrophic fungus in the basidiomycota (Sneh et al. 1991) that causes root, crown and foliar diseases on a wide range of agronomic crops (Couch 1995; Sneh et al. 1991). *Rhizoctonia* spp. are classified into three groups based on the number of nuclei per cell (Ogoshi 1996): multinucleate (MNR), binucleate (BNR) and uninucleate (UNR). Different anastomosis groups (AGs) are present within each group. *Rhizoctonia solani* is highly widespread, with a host range that includes over 500 plant species (Farr and Rossmann 2020). Root and stem rot, seedling damping-off, leaf spot, and foliar web blight are reported worldwide on economically important ornamental species such as *Begonia*, *Catharanthus*, *Chrysanthemum*, *Dianthus*, *Impatiens*, *Osteospermum*, *Pelargonium*, *Petunia*, *Rosa* and *Verbena* spp., among others (Benson and Cartwright 1996; Chase 1991; Holcomb and Carling 2000; Hyakumachi et al. 2005; Rinehart et al. 2007). Symptom development is favored by warm temperatures and high humidity. Damping-off of young seedlings or cuttings in bedding plants commonly develops in a circular pattern within a flat in production or within a bed in the landscape, where the mycelium appears whitish-brown and spiderweb-like on the soil or on the basal leaves (Chase et al. 2018). Brown to black lesions on the crown and base of stems are typical symptoms caused by *Rhizoctonia* spp. on *Begonia, Impatiens* and *Pelargonium,* leading to stunting or death of infected plants. *Rhizoctonia solani* is a very limiting factor in ornamental nurseries in Italy, where several Rhizoctonia diseases have been reported in recent decades (Aiello et al. 2008, 2009a, b; Garibaldi et al. 2003b, 2006, 2009c, d, 2010a, 2013b). Moreover, several bedding plants cultivated in private gardens were reported as susceptible to *R. solani* infections: web blight and crown rot are reported on different *Campanula* and *Lychnis* spp. (Fig. 6) (Garibaldi et al. 2015b, c), crown and stem rot on *Abelmoschus manihot* and *Echinacea purpurea* (Garibaldi et al. 2019a, 2020a), and leaf blight on *Aquilegia*, *Digitalis*, *Hosta*, *Lupinus* and *Salvia* spp. (Garibaldi et al. 2009b, c, d, e, 2010a).

Alternaria leaf spots

Leaf spot caused by *Alternaria* spp. is one of the most frequent diseases of bedding plants propagated through seeds. *Alternaria* is a cosmopolitan genus including several saprophytic and pathogenic species, recently revised into 26 sections (Woudenberg et al. 2013). *Alternaria* sect. *Alternaria* includes major pathogens and contains species that are differentiated based on morphological characteristics (i.e. small and concatenated conidia).

Alternaria alternata is often a saprophyte; however, it is also able to cause disease on several ornamental plants (Thomma 2003). *Alternaria nobilis*, *A. dianthicola, A. saponariae, A. tagetica* and *A. zinniae* are other *Alternaria* species reported on bedding plants such as *Dianthus*, *Saponaria* spp., *Zinnia* and marigold (Garibaldi et al. 2013c; Chase et al. 2018). These species present a gray to olivaceous-black mycelium on artificial media, with typical muriform conidia produced in chains.

Extensive research has been conducted on this disease related to particular hosts such as *Zinnia* and *Pelargonium*, reported from throughout the world. However, Alternaria leaf spots hav also been observed in many new ornamental plant hosts (Matić et al. 2020). Severe outbreaks of leaf spots on new ornamental, medicinal and aromatic plants caused by *Alternaria* spp. occurred during the last two decades in Italy, Greece, Serbia, United States, Canada, Brazil, Uruguay, Mexico, South Africa, Asia

(China, South Korea, India, Iraq, Iran, Pakistan) and Australia (Farr and Rossman 2020). Common symptoms include small, circular, brown to purple (depending on the host species) water-soaked leaf spots which progressively become larger and necrotic. On severely infected plants, defoliation is observed and, occasionally, plant death. *Alternaria* species can be transmitted by seeds, and the recent globalization of the seed trade favors this process (Gullino et al. 2014). Plant debris, weeds and seeds colonized by *Alternaria* species are the sources of overwintering inoculum (Laemmlen 2001).

Other hosts include ornamental and medicinal plants such as *Rudbeckia fulgida* (Garibaldi et al. 2015), *Mentha* × *piperita*, *Salvia elegans,* and *Echinacea purpurea* (Garibaldi et al. 2018 b, c, d; 2020b). More recently, symptoms caused by *A. alternata* occurred on *Plectranthus scutellarioides*, *Ceratostigma willmottianum*, *Digitalis purpurea*, *Phlox maculata* (Fig. 7) and *Alcea rosea* (Fig. 8) (Garibaldi et al. 2019 b, c, 2020b, c, d). *A. arborescens* was reported as a pathogen of *Symphyotrichum novi-belgii* (Garibaldi et al. 2020e). *Campanula medium* and *C. rapunculoides* recently displayed Alternaria leaf spot as small, light-brown, circular spots, becoming irregular and dark brown and enlarging to cover the whole leaf surface, leading to severe plant defoliation (Garibaldi et al. 2019d). Similarly, *Salvia dorisiana*, *S. elegans* and *S. involucrata* were recently affected by Alternaria leaf spot in Northern Italy. Chlorosis and irregular brown necrosis were observed on the margins and blades of infected leaves along with leaf drop (Garibaldi et al. 2018b, 2019e, 2020f; Matić et al. 2020). *Alternaria tenuissima* is a further emerging species recently reported on several bedding plants such as *Begonia semperflorens*, *Coreopsis lanceolata* and *Iris* spp. in China (Li and Liu 2019; Li et al. 2020; Sun et al. 2019; Zhang et al. 2020) and *Echeveria* spp. in Korea (Moon et al. 2019).

Anthracnose

The genus *Colletotrichum* is considered one of the ten most economically important plant pathogens in the world (Dean et al. 2012). *Colletotrichum* spp. are present in a broad range of environments including open fields, greenhouses, and post-harvest warehouses (Cannon et al. 2012).

Until recently, anthracnose was not considered a major disease problem on bedding plants. However, in the last few years, several disease reports have been published highlighting an increased incidence of *Colletotrichum* spp. on ornamental hosts (Chase et al. 2018; Guarnaccia et al. 2019b; McMillan et al. 1996; Polizzi et al. 2011). Among these, *Campanula*, *Cyclamen* and *Salvia* spp. are more severely affected by *Colletotrichum* spp. (Garibaldi et al. 2016a). Round, brown, lightly depressed leaf spots are observed on infected cyclamen leaves. The spots can be numerous and small or may coalesce to form large necrotic patches. Leaf pedicels and flowers can also be affected (Liu et al. 2011). Brown to black, necrotic, circular lesions on leaves of *Campanula trachelium* and *Campanula rapunculoides* were detected in Italy, and strains of *C. lineola* and *C. nymphaeae* were found associated with the disease (Guarnaccia et al. 2020). On *Salvia*, *C. fioriniae, C. fructicola* or *C. nigrum,* and *C. bryoniicola* are responsible for leaf anthracnose on *Salvia leucantha*, *Salvia greggii* and *Salvia nemorosa,* respectively. Although these three species of bedding plants are members of the same genus, the *Colletotrichum* species found to infect them belong to four different species complexes, demonstrating high intraspecific variability associated with this disease (Guarnaccia et al. 2019b). Furthermore, *C. fuscum* has been recently found in Italy as causing leaf anthracnose on *Coreopsis lanceolata* (Fig. 8) (Guarnaccia et al. 2020).

Phoma-like leaf spots

The term “Phoma-like” is a general concept used to identify a broad group of fungal species commonly found on herbaceous stems and leaves (Aveskamp et al. 2010, Chen et al. 2015), including species with no adequate characteristics to be assigned to a genus level (Crous et al. 2004). A recent revision resolved 36 genera including plant pathogens causing plant infection and seeds infestation.

Rudbeckia fulgida is one of the bedding plants known as a host of Phoma-like diseases: infected leaves show extensive and irregular, dark brown, necrotic lesions, slightly sunken and with a well-defined border. Lesions measure 0.5–3 mm in diameter and occasionally coalesce to cover the entire leaf, with consequent leaf drop. Stems can also be affected, leading to death of the plant (Garibaldi et al. 2010b). Similarly, *Salvia nemorosa* and *S. greggii* can present leaf spots caused by *Phoma herbarum* (Fig.8) and *P. exigua* (Garibaldi et al. 2016b; Gilardi et al. 2017). *Phoma novae-verbascicola,* a major species in terms of number of bedding plant hosts, causes typical leaf spots on two *Verbascum* species, *V. blattaria* and *V. nigrum*, where it was reported also as colonizing seeds (Bertetti et al. 2016; Garibaldi et al. 2013d, 2014a). The genus *Campanula* includes several species reported as hosts of Phoma-like fungi, such as *Campanula trachelium* and *C. medium*, infected by *Stagonosporopsis trachelii* (Garibaldi et al. 2015d, 2017b). In India, *Phoma costarricensis* has been reported as responsible of leaf spot on *Delphinium malabaricum* (Patil et al. 2012).

Powdery mildews

Many different genera of powdery mildew fungi occur on bedding plants, among which *Erysiphe*, *Golovinomyces* and *Podosphaera* are prevalent (Chase at al. 2018). Primary infections start from overwintering hyphae in dormant buds, or from ascospores landing on plant tissues (Bélanger et al. 2002). Although the pathogens are not usually seen in greenhouses, they are commonly found in landscapes on bedding plants planted outdoors at the end of the growing season (Chase et al. 2018). The pathogens produce hyphae on the surface of infected tissues that give rise to conidiophores on which asexual propagules (i.e. conidia) are produced (Braun and Cook 2012) and dispersed via air currents and splashing water. Extensive periods of dry conditions and free moisture are both detrimental to conidia germination (Bélanger et al. 2002).

Although powdery mildew fungi do not usually kill their hosts, infected plants show reduced development and photosynthetic ability (McGrath and Shishkoff 2001) and can become unsightly and unmarketable (Chase et al. 2018). In some crops, such as *Phlox* and *Dahlia,* severely affected leaves become distorted, dry out and fall off prematurely (Chase et al. 2018; Farinas et al. 2019; Garibaldi et al. 2011b). Bedding plants frequently affected by powdery mildew include *Begonia*, *Campanula*, *Dahlia*, *Gerbera*, *Petunia*, *Phlox*, *Salvia*, *Verbena*, *Viola* and *Zinnia* spp. (Chase et al. 2018). *Erysiphe begoniicola* (formerly *Microsphaera begoniae*) is a common powdery mildew of begonia on five continents (Amano 1986; Cho et al. 2017; Crous et al. 2000; Pennycook 1989). Although not officially reported, the pathogen is also probably present in North America (Chase et al. 2018). *Erysiphe cruciferarum* was reported on *Cleome hassleriana* in Italy (Garibaldi et al. 2009f). *Podosphaera xanthii* is the major powdery mildew species infecting petunia in both the United States and Europe (Kiss et al. 2008), where *Golovinomyces orontii* is also sometimes found associated with this host (Garibaldi et al. 2007). Another species recently reported on petunia in the United States and also present in Europe is *Euoidium longipes* (syn. *Oidium longipes*) (Kiss et al. 2008; Kiss and Bereczky 2011). *Golovinomyces orontii* was also reported on *Abelmoschus manihot*, *Campanula glomerata* and *Campanula rapunculoides* (Fig. 9), while *G. magnicellulatus* was reported associated with powdery mildew on *Phlox paniculata* in Italy (Garibaldi et al. 2012a, 2016c, 2018e, 2019f) and the United States (Baysal-Gurel et al. 2020; Farinas et al. 2020). The most common powdery mildew reported on zinnia worldwide is *Golovinomyces cichoracearum* (Chase et al. 2018). This species has a very wide host range as it infects more than 2500 hosts, including many ornamentals in the Asteraceae family such as gerbera, orange coneflower, purple coneflower, and Paris daisy (Garibaldi et al. 2008 b, c, 2018 f; Troisi et al. 2010b).

Rust and smut diseases

Several bedding plants species are affected by rust fungi, which are obligate parasites and often host specific. *Puccinia lagenophorae* is present in both the United States and Europe, appearing as raised bumps with orange aeciospores and causing leaf wilt and plant death. This rust species is pathogen of hundreds of plants, such as *Bellis*, *Calendula* and *Gazania* spp. (Hernández et al. 2003). *Puccinia chrysanthemi* and *P. horiana* affect *Chrysanthemum*, whilst *P. pelargonii-zonalis* affects *Pelargonium* spp., (Chase et al. 2018). *Pucciniastrum circaeae* and *P. epilobii* are known as pathogen of *Fuchsia* spp. in Italy, Chile, United States as well as Indonesia (Ferrada et al. 2020; Garibaldi et al. 2012b; Wahyuno et al. 2012), while *Coleosporium campanulae* is a pathogen of *Campanula rapunculoides* (Fig. 10) (Garibaldi et al. 2017c).

White smut diseases, often considered of minor importance, have a great impact on the cultivation of particular bedding plant species. This is the case for leaf smut of *Gaillardia* spp. (Fig. 11) caused by *Entyloma gaillardianum* in California (Glawe et al. 2010), and caused by *Entyloma polysporum* in Virginia (Hong and Banko 2003). The pathogen *Entyloma gaillardianum* causes round, flat, white to tan leaf spots with indistinct margins up to 1 cm in diameter that turned brown and necrotic, followed by necrosis of the entire leaf. It was also reported in Europe (Italy; Garibaldi et al. 2018g). Moreover, *E. dahlia* and *E. calendulae* have been reported on dahlia and cosmos, respectively (Chase et al. 2018).

SUSTAINABLE DISEASE MANAGEMENT

Unique features of the bedding plants industry, such as the high unit value, strongly influence disease management (Daughtrey and Benson 2005; Daughtrey and Buitenhuis 2020; Gullino and Garibaldi 2007). Seeds and cuttings contaminated by several pathogens are often introduced into the production system. When cuttings originate from facilities located in developing countries, the risk of introducing invasive pathogens into new areas increases (Gullino and Garibaldi 2007).

Environmental regulations and water use restrictions are often limiting factors for both producers and consumers. Effective management tools that have low environmental impact and are relatively inexpensive are the preferred choices. This is particularly challenging in the case of crops sold on the basis of aesthetic value. This challenge has led to a comprehensive revision of disease management strategies, which are nowadays almost completely based on prevention.

PREVENTIVE MEASURES

Disease management approaches have shifted in recent years from curative to preventive by adopting sanitation practices and enhancing crop resilience (Fig. 12) (Gullino and Garibaldi 2016; Kruidhof and Elmer 2020). Disease management is increasingly coupled with greenhouse energy saving and technologies for sensing, monitoring and aiding in decision making (Kruidhof and Elmer 2020).

Clean stock and diagnostic tools

Propagation material can be a source of pathogens and must be pathogen free. Pathogens can be exterior contaminants (e.g., *Puccinia anthirrini* on seed of snapdragon, *Fusarium oxysporum* f. sp. *papaveris* on *Papaver nudicaule*) or may be internal (e.g., *Fusarium oxysporum* f. sp. *matthiolae* on matthiola, *Alternaria zinniae* on zinnia, *Heterosporium tropeoli* on nasturtium) (Baker 1972; Bertetti et al. 2015; Wu et al. 2006). Oospores of *Plasmopara obducens* in seeds of balsam impatiens and can produce infected plants (Shishkoff 2019).

Seeds can now be checked by using quick and reliable diagnostic tools and, if needed, treated with chemical, physical or other means (Munkvold and Gullino 2020). Molecular diagnostic tools help with early pathogen identification, and work best when used by the seed industry to check the phytosanitary status of the material (Spadaro et al. 2020). For example, diagnostic tools were developed to rapidly detect *Phytophthora cryptogea* on naturally infected gerbera plants (Minerdi et al. 2008).

Twenty years ago, only a few centers had strong expertise in molecular diagnostic methods (Crous 2005; Schaad et al. 2003). Increased international biosecurity and biodefense investments have helped to keep phytosanitary diagnostics abreast of new developments. The new technologies provide fastermore accurate, and less labor-intensive methods for tracing the movements of plant consignments.

There is a continued drive to provide rapid diagnostic methods for use at points of entry and inspection and to extension services for many important pathogens (Bonants 2014; Thomas et al. 2017; Verrier et al. 2017).

Contaminated seeds can be treated by fungicides, heat, resistance inducers, antagonistic microorganisms, or plant extracts (Gullino et al. 2014). Due to regulatory constraints, at present there is a tendency to replace fungicides with other approaches (Munkvold and Gullino 2020). However, when the pathogen is present inside the seed, only systemic fungicides and heat are effective for eradication. For bulb crops such as gladiolus and iris, hot water treatments provided promising results for disease control (Gullino 2012).

Cultural practices

Monitoring and control of environmental parameters

For bedding plants, growers can exert some control over environmental conditions to optimizing plant growth and manage pathogens. In the most sophisticated production facilities, disease management is greatly enhanced by monitoring and controlling temperature, light, humidity, water, ventilation, carbon dioxide, and crop nutrition with high precision. Manipulating the interactions of temperature and humidity is important in the control of foliar diseases, while rhizosphere moisture and temperature are relevant for root and stem diseases.

Dew deposition in the greenhouse, which is favorable for downy mildews, rusts, and Botrytis blight, is common on cool nights following warm, humid days. Regulating day and night atmospheres is important for disease control and also helps in reducing the total amount of fungicide sprayed (Gullino and Garibaldi 2016; Hausbeck and Moorman 1996). *Botrytis cinerea* on fuchsia was managed with specific climate and/or ventilation manipulation (Friedrich et al. 2005). For gray mold (*B. cinerea*) management, ventilation alone helps, minimizing the risk of epidemics by permitting good air movement.

Heating and ventilating at the same time or using a dehumidification device allows greenhouse growers to reduce relative humidity (Cámara-Zapata et al. 2019).

Avoiding temperatures conducive to *Phytophthora infestans,* and reducing moisture reduced late blight on petunia (Becktell et al., 2005). On rose, *Peronospora sparsa* is now much less important than in the past due to better control of greenhouse relative humidity, as well as the availability of effective fungicides (Gullino and Garibaldi 2016).

Root-zone or soil heating can be accomplished with either floor or bench heating systems. Altered greenhouse and bench design can improve air movement, thus reducing the risk of diseases. Through-the-bench air movement is, perhaps, the simplest but most neglected means of reducing seedling rots in high-density systems.

Development of Fusarium root and crown rot incited by *Fusarium hostae* in container-grown hostas is affected by the type of wounding that occurs during propagation, container mix content, watering schedule, and temperature. Peat or peat-bark mixes reduced disease incidence and severity, and disease was higher on plants growing in container mix and at moderate (20-25°C) temperatures (Wang and Jeffers 2002).

The application of lime to the medium increases pH and suppresses Fusarium wilts (Elmer 2012), as has been observed in crops such as chrysanthemum (Engelhard and Woltz 1973) and gerbera (Gullino and Garibaldi 2016).

Shading is often used by growers when crops are wilting, but its effect is mostly on temperature rather than light intensity. For severe root rot of lavender caused by *Phytophthora nicotianae* var. *parasitica*, a ≥50% reduction in rot incidence was achieved by growing plants under shade. The effect was attributed to reduced heating of the root zone in black pots used by growers; white containers might also have benefits. In contrast, shading strongly increases the severity of powdery mildew caused by *Golovinomyces cichoracearum* on aster (Gullino and Garibaldi 2016). Each host-pathogen system may have its own unique response to light.

Soilless cultivation and treatments

If bedding plants are grown with recirculating irrigation systems, the spread of diseases in soilless cultivation systems can be suppressed by adopting proper disinfection methods for the recirculating solution, such as slow sand filtration. Closed recirculating soilless systems represent an interesting environment for exploiting innovative disease management options. Increasing the electrical conductivity of the nutrient solution and using potassium silicate amendments have proved effective against a number of foliar and soil-borne diseases such as powdery mildews, downy mildews, leaf spots and Fusarium wilts (Garibaldi et al. 2014b; Gullino et al. 2015). A higher level of electrical conductivity and deposition of amorphous silica in the cell wall could result in an increase in the production of lignin that could contribute to limiting pathogen penetration within the plant cell (Gullino et al. 2015; Gullino and Garibaldi 2016). The ability of electrical conductivity to induce resistance against *Fusarium oxysporum* f. sp. *cyclaminis* on cyclamen have been documented by Elmer (2012) using chloride salts.

Soilless systems used for bedding plant production allow for more precise manipulation of microbiological conditions. This is achieved through the application of microorganisms able to colonize the root system of plants grown under a strictly controlled environment. Suppressiveness of re-used substrates in soilless cultivation has many possible practical applications (Clematis et al. 2009). Antagonistic microorganisms isolated from soilless hydroponic systems have proven effective against Fusarium wilt of rocket (Srinivasan et al. 2009) and *Pythium ultimum* on cucumber (Liu et al. 2009). Although utilized for field crops and vegetables, the use of organic amendments for disease control is not widespread in bedding plant production, mainly because bedding plants are not usually produced in soil. In the future, organic amendments may have a role in garden plantings of bedding plants.

Resistance inducers provide effective and long-term management of several soil-borne pathogens on vegetable crops (Gilardi et al. 2019). Their ability to strengthen plant defense and contribute to reduced use of fungicides (Shoresh et al. 2010; Walters et al. 2013), is currently being investigated.

Resistance inducers are in continuous development. However, several aspects, such as pathogen life-style, plant developmental stage, environmental and climatic conditions (temperature, relative humidity, disease pressure), timing, formulation and type of application, contribute to highly variable efficacy results (Walters and Fountaine 2009). A better understanding of the mode of action is needed. Thus application of resistance inducers should be further investigated to improve disease control efficacy in bedding plants.

BOX 1

Substrate suppressiveness

Suppressiveness, a phenomenon that has been well described for soils, also occurs in the soilless substrates used in floriculture (Hadar 2011; Pugliese et al. 2015). It has been exploited for practical use against Fusarium wilts on carnation, cyclamen and bulb crops, among others (Garibaldi and Gullino 1990; Gullino et al. 2015).

Much research has been carried out on suppressiveness of peat, alone or mixed with other substrates. Sphagnum peat mixes did naturally suppress diseases caused by soil-borne pathogens, but within a few weeks after potting they became conducive to diseases (Hoitink and Boehm 1999). Bacteria and fungi contributed to the suppression of root rots and wilts in peat mixes (Tahvonen and Kuuluvainen 1993). Since light peat decomposes in pots during production and the disease suppression effect is lost, amendments of decomposed peat mixes with microorganisms should consider the decomposition state (Hoitink and Locke 2012). Mixing light peat with more decomposed peat, at a 1:1 ratio, resulted in commercial sphagnum potting mixes capable of providing, through suppressiveness, control of soil-borne pathogens for most greenhouse crops (Hoitink and Boehm 1999).

In the case of substrates, when hardwood bark (composted or not) is used, improved plant growth is generally observed, especially in potted plants. Suppressiveness and improved vigor of plants in such bark substrates result from the physical characteristics of bark composts and from higher levels of antagonists supported by these composts (Hoitink and Boehm 1999). Peat mixes also support well the introduction of biocontrol agents or the addition of composts (Hoitink and Locke 2012). Growing mixes fortified with *Trichoderma hamatum* 382 controlled Botrytis blight on geranium (Olson and Benson, 2006) and begonia (Horst et al. 2005). The same biocontrol agents (BCA) added to potting mixes controlled Fusarium wilt of cyclamen (Hoitink and Locke 2012). During the past 25 years, recycling of composted organic wastes has been adopted for environmental, economic and production reasons. From an environmental point of view, compost is considered an attractive peat substitute, after increasing concerns about the impact of peat extraction, and the damage to peat land natural habitats by the horticulture industry (Silva et al. 2007). The cost of composts can be lower than that of peat. Composted materials can suppress soil-borne pathogens (Noble and Coventry 2005; Pane et al. 2011; Pugliese et al. 2015; Termorshuizen et al. 2006). The consistency of disease control is improved when compost is enriched with selected microorganisms (Pugliese et al. 2011).

The suppressive capacity of compost against soil-borne pathogens has been demonstrated in several studies leading to greater production efficiency and reduced non-target effects (Garibaldi 1988; Hadar 2011; Hoitink and Boehm 1999; Noble 2011; Noble and Coventry 2005). Low rates of compost in growing media are generally indicated in order to avoid negative growth effects and phytotoxicity caused by high pH and electrical conductivity, and other phytotoxic compounds present in composts (Sullivan and Miller 2001). However, it is generally necessary to include at least 20% v/v of compost in containers in order to observe a suppressive effect (Table 2). Cases of increase of disease severity caused by composts used in containers have also been reported. A 50% spruce bark compost increased black root rot caused by *Thielaviopsis basicola* in poinsettias and Fusarium wilt of cyclamen, compared to a peat substrate (Krebs 1990). Highly saline composts were reported to enhance *Pythium* and *Phytophthora* diseases, while composts with higher nitrogen or ammonium content enhance Fusarium wilts (Hoitink et al. 2001). Success or failure of compost for disease control depends on the nature of the raw materials from which the compost was prepared, on the composting process used, and on the maturity and quality of the compost (Termorshuizen et al. 2006).

> Control of soil-borne diseases with organic amendments must be viewed as part of a systems approach where several aspects of the impact of crop production practices on resident soil microbial communities are addressed. New approaches to monitor how microbial community structures in soil change as a result of organic amendments may lead to a better understanding of which changes in microbial communities are responsible for conferring the disease suppressive effects (Cucu et al. 2019, 2020). This may eventually lead to improved, reliable disease controls for bedding plants, resulting from organic amendment of growing media in greenhouse production.

Box 2

Regulatory control

Quarantine restrictions and eradication measures are sometimes necessary in order to avoid the spread of pathogens that can severely affect the production of certain economically important crops (Ebbels 2003; Gamliel and Fletcher 2017).

State, regional and international laws and regulations govern the production, sale and transportation of ornamental plants. Measures designed to control the introduction of foreign pests are enforced in several countries. Domestic and international quarantines restrict the movement of specific plant materials at risk of carrying pests in order to prevent or delay their introduction. These quarantines often require cultural practices or chemical treatments to satisfy movement requirements (Guarnaccia et al. 2019c). Quarantine regulated pest lists are available in most regions (Ebbels 2003; Stebbins and Johnson 2001). Many pathogens are not detected because they are present as latent infections in plants. Therefore, missed detections in routine inspection are highly possible (Slippers and Wingfield 2007). Border controls are less effective than they should be because local quarantine lists of pathogens are often found only in inaccessible national databases or government publications. Thus, the quarantines may not be supported by relevant data and nomenclature of the species in question may not be up to date (Crous et al. 2016).

Quarantines have been used, for instance, to limit movement of rust pathogens of geranium, chrysanthemum, daylily and gladiolus in several countries. Quarantines proved effective in the United States as well as in Australia in the case of chrysanthemum white rust, incited by *Puccinia horiana* (Bonde and Rizvi 1995), and gladiolus rust, incited by *Uromyces transversalis* (Beilharz et al. 2001). The same happened in Colombia, where in the early 1980s a strict eradication and control campaign was implemented to keep all chrysanthemum exports free of *P. horiana* (Ortega 1999). If white rust was detected on plant material imported from Colombia, United States imports would be halted. In other cases, quarantine measures were ineffective. For instance, containment of *Puccinia hemerocallis,* the causal agent of daylily rust, in the United States failed due to the widespread movement of plants by hobbyists and nurseries (Williams-Woodward et al. 2001). Also, geranium rust, caused by *Puccinia pelargonii-zonalis*, became endemic in Europe and the United States despite quarantine restrictions and the destruction of infected plants (Wise et al. 2004).

Quarantine restriction and eradication efforts can be costly and have a significant economic impact on floriculture production, and, as noted, are not always effective. However, the fact that ornamental plants can vector new pathogens, potentially causing losses on other crops, must be considered in assessing the need for enhanced quarantine guidelines.

Research needs and future outlook

Many important problems of the bedding plant industry are unresolved and new ones are emerging as the industry undergoes more changes in production, marketing and shipping procedures. Major changes will include more widely adopted mechanization and automation systems for improved crop management and the continuous introduction of new species, according to consumers' taste. Some of those changes will affect the severity of diseases, thereby challenging plant pathologists.

The phytopathology of bedding plants encompasses a wide range of diseases on an immense variety of crops, with great opportunity for imaginative research and development of new methods for disease management, mostly based on preventive measures. The relatively low cost of the final product as compared to other floriculture crops is a strong constraint and forces growers to avoid too many external inputs. The energy crisis, along with increasing restrictions on the use of pesticides, and the effect of climate change, along with the constant introduction of new crops from new areas around the world, pose new challenges to researchers and growers. In the future, interventions taking place at the production level, particularly at the seedling and plug production stage—those able to increase plant resilience—will be the most useful. Plant pathologists will have to work more closely with horticulturists to ensure that new management practices have beneficial or, at worse, neutral effects on plant health. The global movement of bedding plants is leading to alarming introductions of new plant pathogens into areas where they were previously not present. The detection of these organisms will lean on fast and accurate molecular techniques for quarantine and screening in the future (McTaggart et al. 2016). Methods to improve the accuracy and speed of field and laboratory diagnosis have been developed and need to be implemented more extensively (Thomas et al. 2017; Spadaro et al. 2020). The use of pathogen-free propagation material obtained through sanitation, clean growing media, pots, containers, or benches, disinfected mostly with steam, will continue to be important in the management of soil-borne diseases. There is a demand for more effective disease control agents (biological microbials and natural materials). More research in the field of biological control is certainly needed in order to realize its potential. New approaches to monitor how microbial community structures in soil change as a result of amendments may lead to a better understanding of which changes in microbial communities are responsible for conferring the disease suppressive effects of compost (Cucu et al. 2019). This may eventually lead to improved and more reliable disease control resulting from compost amendment of soil, sand or peat, both in container crops in greenhouses and in the field (Noble and Coventry 2005; Noble 2011). Research on etiology, monitoring, modelling and breeding for resistance is also needed.

Finally, there is a strong need for improved information flow among researchers, extension personnel, growers and consumers, for maintaining close links between the production and marketing sectors of the industry, and for giving more attention to consumers' needs. Due to the increased attention paid by consumers to environmental issues, efforts should be made to educate them to make wise choices. Unfortunately, few funding programs are designed specifically for ornamental pathology research and most agencies still consider ornamentals as a niche sector. This attitude fails to consider the fact that a number of techniques developed specifically for the ornamental industry (i.e. culture-indexing cuttings, apical meristem culture, improvements in tissue culture methods, virus indexing by grafting on indicator plants, soil steaming, soilless cultivation) have also proved useful for controlling diseases on other crops (Baker and Linderman 1979; Gullino and Garibaldi 2005).

The unique nature of the ornamental industry also requires very well-trained extension specialists. Unfortunately, during the past decade, many university courses devoted to diseases of ornamentals have disappeared (Fletcher et al. 2020). The ornamental industry also needs highly qualified support by extension specialists, which is often missing.

The high economic and aesthetic value of bedding plants make them deserving of more attention by plant pathologists and, more generally, by researchers, while their beauty will continue attracting consumers. Diseases of bedding plants and other ornamentals will thus continue to provide a fruitful and stimulating field of study for plant pathologists, and research in this field will hopefully no longer be considered as focused on the outer fringes of agriculture.

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Table 1. Pathogenicity of *Fusarium oxysporum* strains isolated from orange coneflower on different bedding plant hosts in the *Asteraceae*. The data are expressed as disease severity (0-100) and compared to reference strains of *F. oxysporum* f. sp. *chrysanthemi* at the end of two trials (from Matić et a. 2018).

Isolates	Trial 1												Trial 2								
	Orange coneflower			African daisy (cv. Variegata Bianca)			Chrysanthemum (cv. SupraQuivre)			Paris daisy (cv. Stella 2000)			Orange coneflower			Chrysanthemum (cv. Polochon Cognac)			Gerbera (cv. Carambole)		
F. oxysporum f. sp. *chrysanthemi* DB32	59.2	b[a]	S[b]	55.0	b	S	21.7	b	MS	84.2	b	HS	37.5	ab	MS	35.0	ab	MS	87.5	b	HS
F. oxysporum f. sp. *chrysanthemi* FC32	64.2	b	S	80.0	b	S	19.2	b	PR	87.5	b	HS	100.0	c	HS	40.0	b	MS	53.1	b	S
F. oxysporum f. sp. *chrysanthemi* DB23	60.0	b	S	65.0	b	S	39.2	b	MS	95.8	b	HS	47.5	a-c	MS	35.0	ab	MS	90.6	b	HS

F. oxysporum f. sp. *chrysanthemi* DB43	77.5	b	S	69.2	b	S	44.2	b	MS	92.5	b	HS	43.8	a-c	MS	30.0	ab	MS	68.8	b	HS
F. oxysporum IT22	64.2	b	S	51.7	b	S	38.3	b	MS	92.5	b	HS	37.5	ab	MS	55.0	b	S	71.9	b	HS
F. oxysporum IT23	nt[c]	nt	Nt	nt	nt	nt	nt	nt	Nt	nt	nt	nt	56.3	a-c	S	50.0	b	MS	62.5	b	HS
F. oxysporum IT24	63.3	b	S	75.0	b	S	30.0	b	MS	93.3	b	HS	56.3	a-c	S	50.0	b	MS	75.0	b	HS
F. oxysporum IT25	66.7	b	S	64.2	b	S	36.7	b	MS	96.7	b	HS	68.8	bc	S	45.0	b	MS	62.5	b	HS
Non inoculated	0.0	a	-	0.0	a	-	0.0	a	-	0.0	a	-	0.0	a	-	0.0	a	-	0.0	a	-

[a] Values followed by the same letter are not significantly different (P = 0.05) according to Tukey's multiple range test;

[b]R = Resistant (disease index 0-5); PR = Partially Resistant (disease index 6-20); MS = Moderately Susceptible (disease index 21-50); S = Susceptible (disease index 51-75); HS = Highly Susceptible (disease index 76-100);

[c]nt = not tested.

Table 2. Effect of municipal compost against *Phytophthora* spp. on ornamentals (from Pugliese et al. 2012).

Substrate	Pathogen	% (v/v) Compost	***Phytophthora cinnamomi* on azalea**		***Phytophthora nicotianae* on *Skimmia japonica***			
			Trial 1	**Trial 2**	**Trial 1**		**Trial 2**	
			% healthy plants	**% healthy plants**	**% healthy plants**	**Biomass (g)**	**% healthy plants**	**Biomass (g)**
Peat + Compost	Yes	10	92 a*	56 bc	42 d	3.8 c	53 c	11.4 c
Peat + Compost	Yes	20	79 ab	10 d	58 bc	5.3 abc	87 bc	16.2 bc
Peat + Compost	Yes	40	89 ab	44 cd	75 abc	7.1 ab	90 ab	21.8 b
Peat + Compost	No	20	96 a	93 a	100 a	8.1 a	100 a	22 b

Peat	No	0	100 a	100 a	100 a	7.2 ab	100 a	29.2 a
Peat	Yes	0	69 b	6 d	45 d	3.4 c	50 c	9.5 c
Peat + Metalaxyl-M (25 ml/m3)	Yes	0	92 a	80 ab	89 ab	7.7 a	100 a	25.8 ab

* Tukey's HSD test (P < 0.05)

Figure captions

Figure 1. Examples of the wide variety of species grown as bedding plants.

Figure 2. Some bedding plant diseases caused by different groups of pathogens.

Figure 3. Evaluation of different *Asteraceae* species for susceptibility to *Fusarium oxysporum* f. sp. *chrysanthemi*.

Figure 4. Symptoms of Fusarium wilt on cyclamen.

Figure 5. Symptoms of downy mildew caused by *Peronospora digitalidis* on *Digitalis purpurea*.

Figure 6. Collapse of *Lychnis coronaria* plant caused by *Rhizoctonia solani*.

Figure 7. Severe attack of *Alternaria alternata* causing leaf spot on *Phlox maculata*.

Figure 8. Leaf spot caused by *Alternaria alternata* on *Alcea rosea*.

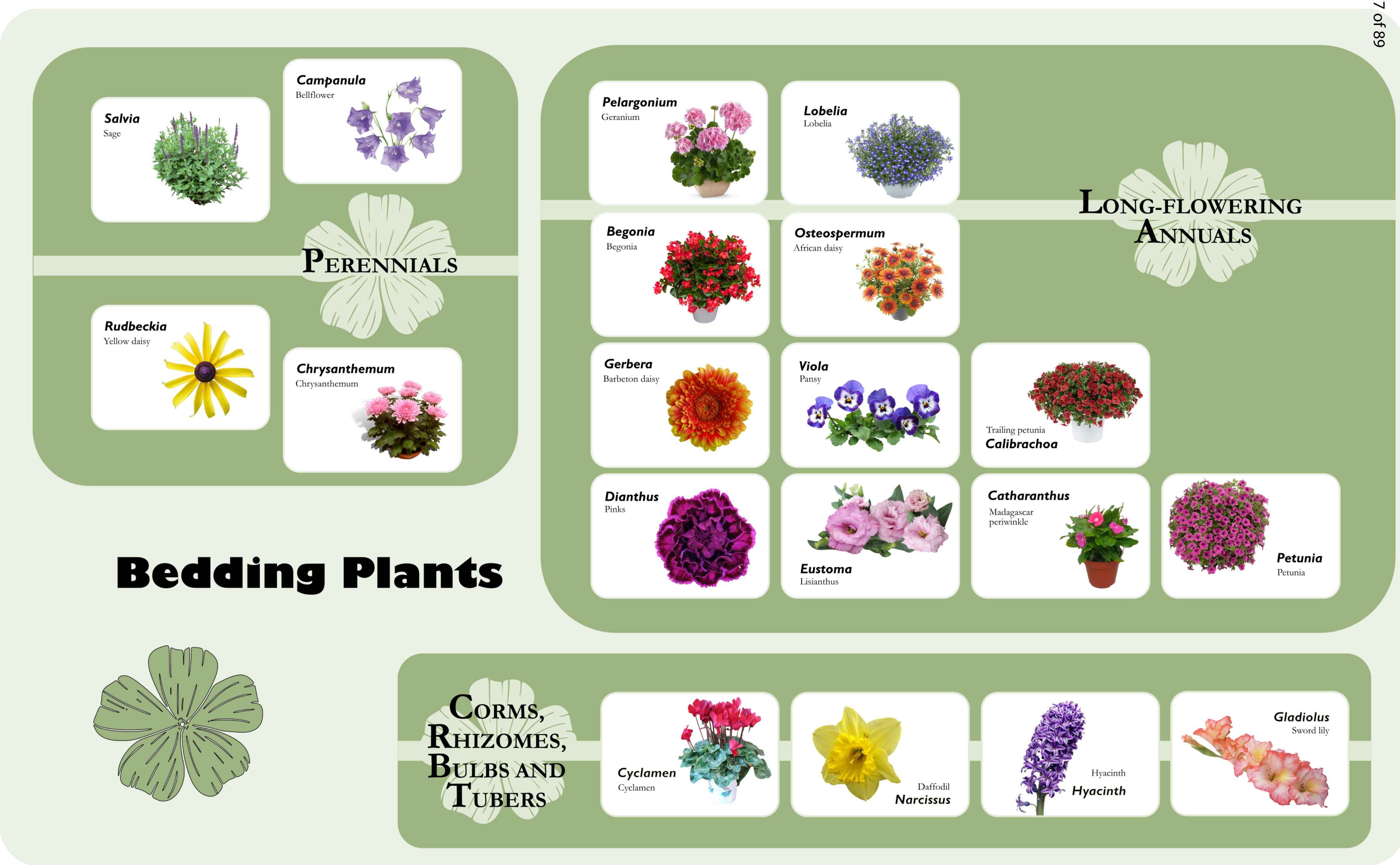
Figure 9. Leaf anthracnose caused by *Colletotrichum fuscum* on *Coreopsis lanceolata*.

Figure 10. Powdery mildew caused by *Golovinomyces orontii* on *Campanula rapunculoides*.

Figure 11. Rust on *Campanula rapunculoides* caused by *Coleosporium campanulae*.

Figure 12. Round, white leaf spots on *Gaillardia aristata* caused by *Entyloma gaillardianum*.

Figure 13. Smart prevention measures for sustainable disease management.


Bedding Plants
Perennials
Salvia
Sage
Campanula
Bellflower
Rudbeckia
Yellow daisy
Chrysanthemum
Chrysanthemum
Long-flowering Annuals
Pelargonium
Geranium
Lobelia
Lobelia
Begonia
Begonia
Osteospermum
African daisy
Gerbera
Barbeton daisy
Viola
Pansy
Trailing petunia
Calibrachoa
Dianthus
Pinks
Eustoma
Lisianthus
Catharanthus
Madagascar periwinkle
Petunia
Petunia
Corms, Rhizomes, Bulbs and Tubers
Cyclamen
Cyclamen
Daffodil
Narcissus
Hyacinth
Hyacinth
Gladiolus
Sword lily

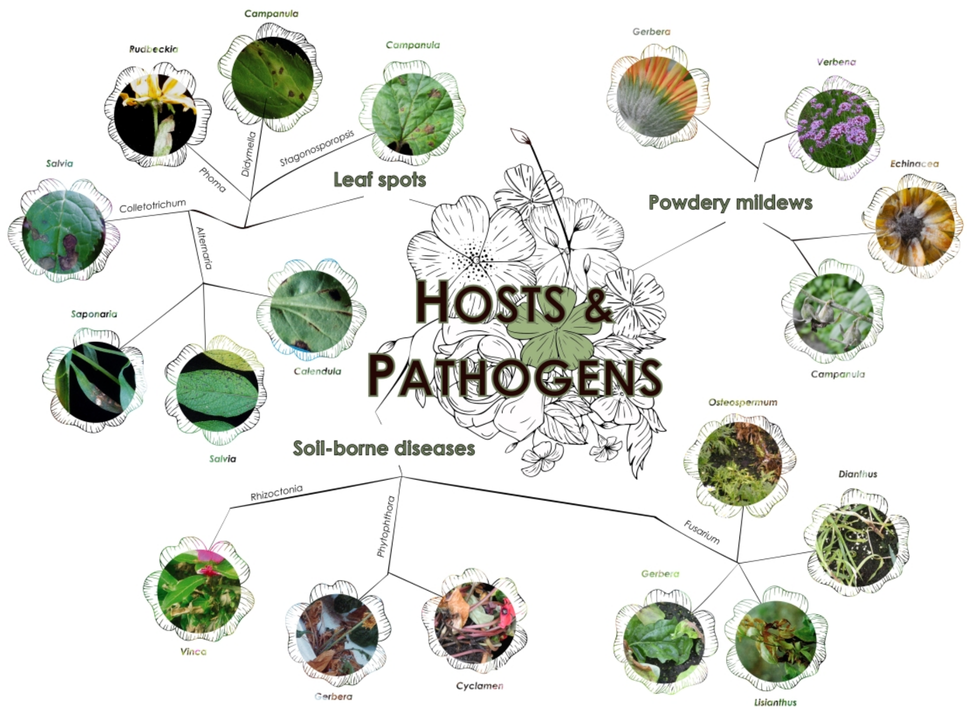


Figure 2. Bedding plant diseases caused by different groups of pathogens

Figure 3. Evaluation of differential Asteraceae species for susceptibility to Fusarium oxysporum f. sp. chrysantemi

179x123mm (300 x 300 DPI)

Figure 4. Symptoms of Fusarium wilt on cyclamen

308x231mm (300 x 300 DPI)

Figure 5. Symptoms of downy mildew caused by Peronospora digitalis on Digitalis purpurea

295x224mm (300 x 300 DPI)

Figure 6. Collapse of Lychnis coronaria plant caused by Rhizoctonia solani

682x914mm (72 x 72 DPI)

Figure 7. Severe attack of Alternaria alternata causing leaf spot on Phlox maculata

647x901mm (72 x 72 DPI)

Figure 8. Leaf spot caused by Alternaria alternata on Alcea rosea.

219x163mm (300 x 300 DPI)

Figure 9. Leaf anthracnose caused by Colletotrichum fuscum on Coreopsis lanceolata.

114x158mm (300 x 300 DPI)

Figure 10. Powedery mildew caused by Golovinomyces orontii on Campanula rapunculoides

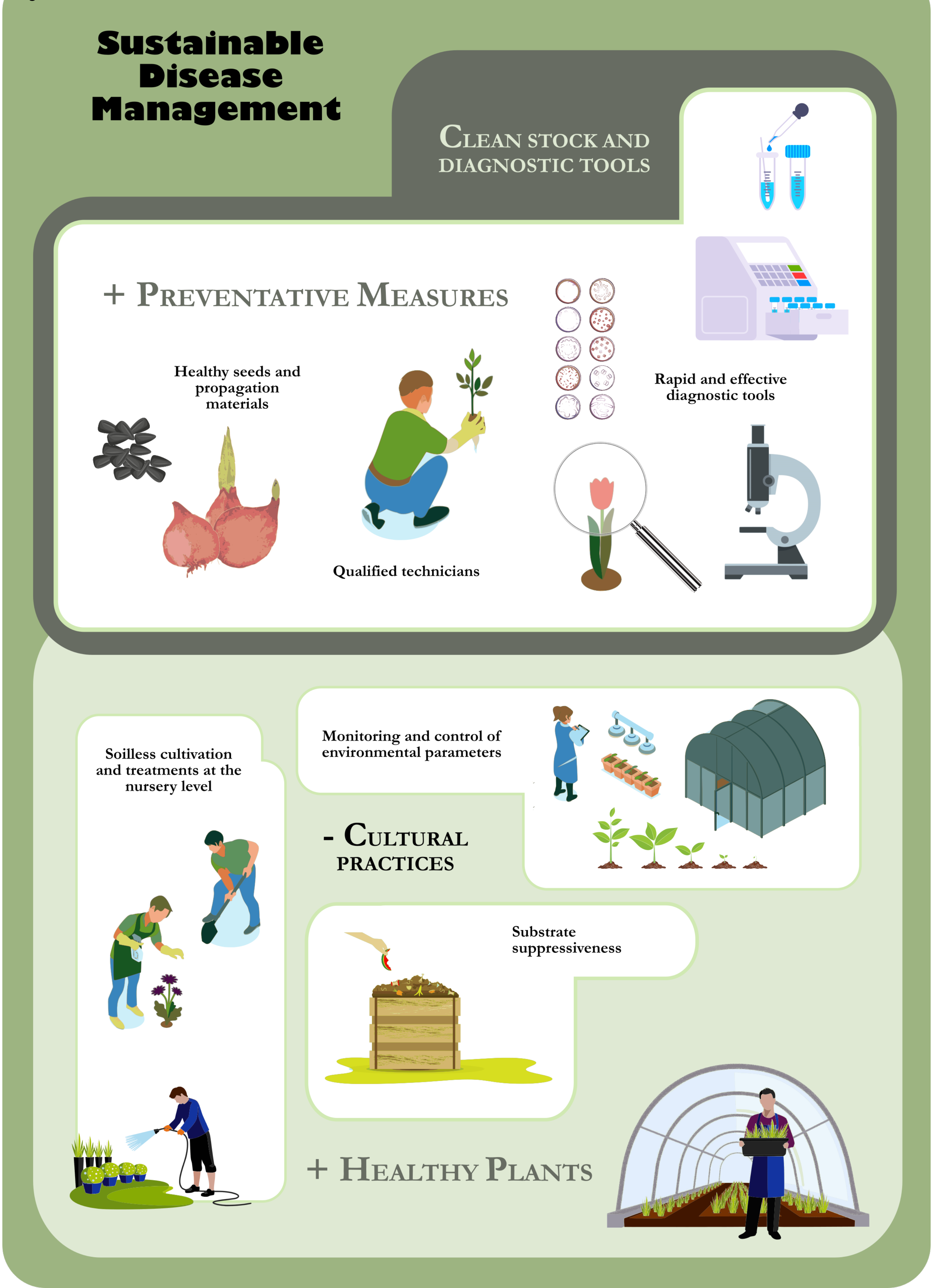
308x231mm (300 x 300 DPI)

Figure 11. Rust on Campanula rapunculoides caused by Coleosporium campanulae

254x338mm (300 x 300 DPI)

Figure 12. Round and white leaf spots on Gaillardia aristata caused by Entyloma gaillardianum

914x682mm (72 x 72 DPI)


Sustainable Disease Management
Clean stock and diagnostic tools
+ Preventative Measures
Healthy seeds and propagation materials
Qualified technicians
Rapid and effective diagnostic tools
Soilless cultivation and treatments at the nursery level
Monitoring and control of environmental parameters
- Cultural practices
Substrate suppressiveness
+ Healthy Plants