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Mycotoxins in harvested fruits and vegetables: Insights in producing fungi, biological role, conducive conditions, and tools to manage postharvest contamination

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ABSTRACT

The postharvest life of fruits and vegetables is influenced by several parameters, such as physiological properties and biotic/abiotic stresses. In particular, a consistent portion of the product is lost, mainly due to fungal diseases, which represent a concern not only to retailers but also to consumers, due to the presence of mycotoxins. Indeed, some species of postharvest *genera*, *i.e. Aspergillus*, *Penicillium,* and *Alternaria*, produce toxic secondary metabolites, which pose a health risk to humans and animals, so that maximum content in harvested commodities and derived products have been established for certain toxins by national and international organizations. Although some mycotoxins are poisonous to competing microorganisms or plants, their biological role is still unclear. Recent studies support their involvement in disease onset/development, so that a reduction in mycotoxin production might have a disease control perspective. Indeed, the use of synthetic fungicides is not always possible or effective in postharvest, because of restrictions on residue content and the appearance of resistant strains. Moreover, the application of suboptimal concentrations of fungicides may even increase mycotoxin biosynthesis. Thus, the demand for alternative control means (*e.g.* microbial antagonists, natural or generally regarded as safe compounds, and physical means) is growing. In this review, a synopsis of the main postharvest mycotoxigenic *genera* is given with particular reference to their control.

1. Introduction

Postharvest diseases of fruits and vegetables currently cause the loss of 35–55% of the total production, with significant differences among the geo-economic areas (*e.g.* 55% in developing countries). These losses occur at quantitative, especially in the case of mycotoxin-contamination, as well as qualitative and safety level (Aulakh and Regmi, 2013). Mycotoxins are low molecular weight compounds produced by certain fungal genera and species, able to elicit a toxic response in humans and other vertebrates through a natural exposure at very low amounts (Gallo et al., 2015). Several national organizations worldwide made a severe normative effort to regulate their content in feed- and foodstuffs. Indeed mycotoxins are often very stable molecules and, thus could "resist" or "withstand" processing.

The present review focuses on the main mycotoxins commonly present in the postharvest phase of fruits and vegetables and their producing fungal *genera* involved in related spoilage, namely *Alternaria, Aspergillus,* and *Penicillium* (Fig. 1). Emphasis has been given to the mycotoxin biological role and the main parameter influencing the biosynthesis. In addition, main strategies for controlling mycotoxin presence in postharvest are presented.

1.1. Alternaria

The genus *Alternaria* contains many species that are pathogens to various commodities. For instance, *Alternaria brassicae* infects cole crops and leads to *Alternaria* blight, *Alternaria* dauci and *Alternaria radicina* infect carrots and can lead to carrot black rot, or *Alternaria alternata* causes citrus brown spot (Fig. 2A). In a recent paper, Woudenberg et al. (2015) proposed to reclassify the 26 *Alternaria* sections in 11 phylogenetic species and 1 species complex. Thirty-five morphospecies, undistinguishable even on a multi-gene phylogeny, were synonymised under *A. alternata*.

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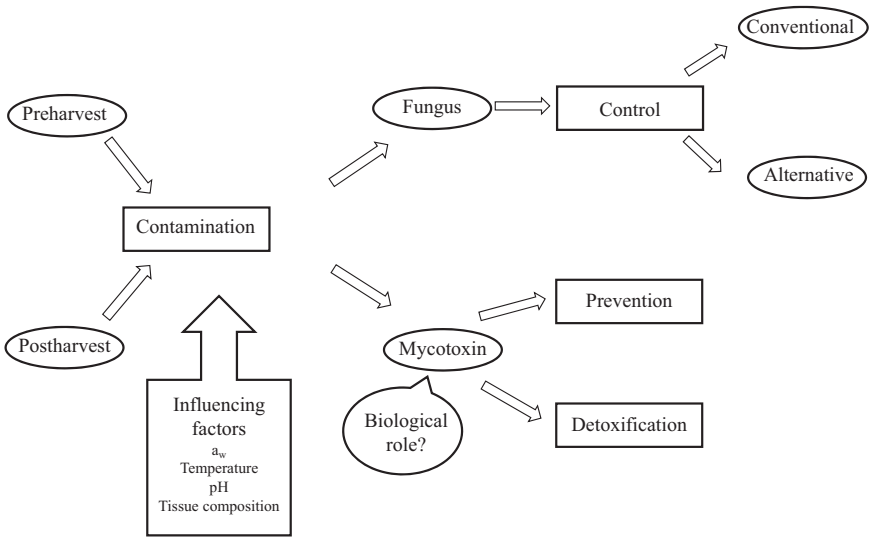

Fig. 1. Flowchart resuming the main contents of the review and their links.

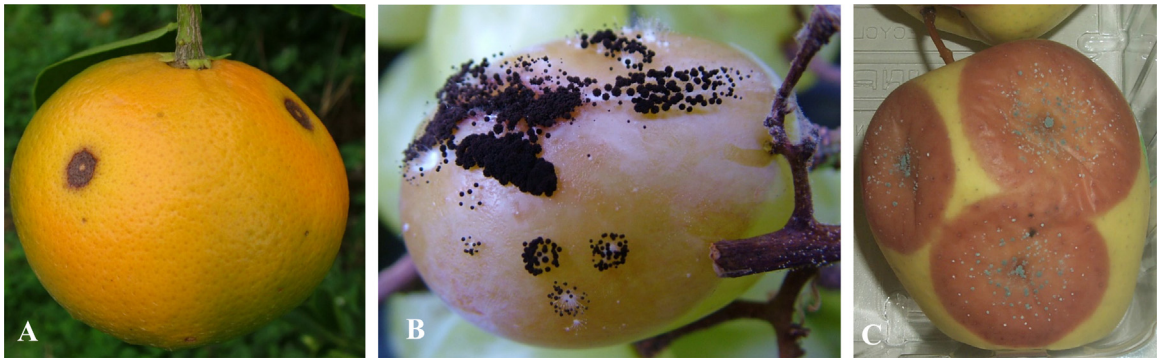

Fig. 2. *Alternaria* spp. on mandarin (A); *Aspergillus* spp. on table grape cv. Italia (B); *Penicillium* spp. on "Golden Delicious" apple (C).

A. alternata is the most important within the genus, as regards to mycotoxin contamination of fruits and vegetables. Several plant-specific pathotypes exist that in the field can infect apples, strawberries, pears, melon, tomatoes, citrus, *etc.* (Logrieco et al., 2009a). However, *A. alternata* also occurs in a saprotrophic form, which usually cannot infect living plants, but rather harvested fruits and vegetables. A difference between the two forms is a small conditionally dispensable chromosome (CDC), which carries host specific pathogenicity factors required for infecting living plants. In case of the tomato-specific *A. arborescens* (former *A. alternata* f. sp. *lycopersici*), the CDC carries genes for the biosynthesis of AAL toxin (Hatta et al., 2002), which represents a pathogenicity factor for tomatoes. In fact, mutants deficient in AAL toxin biosynthesis proved to be unable to infect tomatoes (Akamatsu et al., 1997). Non-pathogenic *A. alternata* strains do not carry this CDC and thereby AAL biosynthesis genes as *alt*1, which codes the AAL polyketide synthase (Akagi et al., 2009). However, saprotrophic strains of *A. alternata* can acquire pathogenicity by transfer of the CDC chromosome (Akagi et al., 2009). A similar situation emerged in the *Alternaria* – apple pathosystem. The apple pathotype *A. alternata* f. sp. *mali* produces AM toxin, a cyclic peptide, as host specific pathogenicity factor (Tournas and Stack, 2001). This peptide interacts with the chloroplasts and the cell wall/membrane of the host and supports infection by the fungus (Johnson et al., 2000).

In terms of food safety of fruits and vegetables, the production of host specific toxins from pathogenic *A. alternata* strains seems not to be a real problem (Mamgain et al., 2013), albeit the AAL toxin resembles in structure the fumonisins, important mycotoxins produced by *Fusaria* (Desjardins and Proctor, 2007). A much more important problem are saprotrophic strains of *A. alternata*, which colonizes harvested plant products and can produce reasonable amounts of certain mycotoxins, which exert poisonous effects after consumption by humans.

1.2. Aspergillus

Aspergillus is a genus in which several saprotrophic and pathogenic species are present. Amongst these, *Aspergillus* sect. Flavi (specifically *A. flavus, A. parasiticus*), *Aspergillus* sect. Nigri (specifically *Aspergillus niger, A. tubingensis, Aspergillus carbonarius*) (Fig. 2B), *Aspergillus* sect. Circumdati (specifically *A. ochraceus, A. westerdijkiae*) are plant (opportunistic) pathogens and mycotoxin producers. Some of these species infect entire plant organs, especially seeds and fruits, where they usually produce a huge amount of secondary metabolites, specifically mycotoxins such as aflatoxins (AFs), ochratoxin A (OTA), fumonisins (FBs) and patulin (PAT) (Amaike and Keller, 2011; Scott, 2012; Ostry et al., 2013; Snini et al., 2014; Sanzani et al., 2015). They are produced during the entire cycle of infection, even if most part could be secreted during the storage of seeds and fruits (Sweeney and Dobson, 1998). AFB1 is amongst the most dangerous compounds of natural origin.

Do fungi infecting commodities just during postharvest phase actually exist? Considering the specific "story" of some *Aspergilli*