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# Alternative management technologies for postharvest disease control: The journey from simplicity to complexity

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## Abstract

Finding safe and effective alternatives to synthetic fungicides for reducing postharvest losses of harvested commodities has been a focus of much research over the past three decades. Identifying alternatives that are widely accepted and commercially viable has, however, been a challenge. The search to identify alternative approaches to postharvest disease management must be viewed in relation to a complex regulatory environment, the need to address disease problems in a wide array of commodities and conditions, industry and consumer acceptance, and last but not least, commercial viability. In order for companies to invest in new technologies, they must be able to clearly see both the value of a product and the financial return on their investment. The present review attempts to highlight how the search for alternative postharvest disease management technologies has been a journey from simplicity to complexity. Plant pathologists developing alternative technologies are slowly moving away from the "silver bullet" concept where a single intervention can be used to control a disease to viewing plant disease as a process where multiple interventions may be required at different points in the disease process. Over the past thirty years, alternatives have moved from the simple idea of applying high concentrations of biocontrol agents to a harvested commodity, to using a wide array of other alternatives, and integrating them together into a systems approach based on the multiple decrement or multiple hurdle concept. The ease of sequencing genomes and obtaining related genotypic, transcriptomic, proteomic, and metabolomic information is leading to the development of new commercial technologies where problems are solved "biologically."

*Keywords:* Biological control; Multiple decrement concept; Natural products; Physical treatments

## Introduction

*And so, from hour to hour we ripe and ripe, And then from hour to hour we rot and rot, And thereby hangs a tale.* **William Shakespeare** (As You Like It, Act II, Scene vii)

Finding safe and effective alternatives to synthetic, chemical fungicides for reducing postharvest losses of harvested commodities has been the focus of much research over the past three decades (Table 1). Finding alternatives that are widely accepted and commercially viable has, however, been a challenge. Nevertheless, there is a real imperative to continue this line of research, since regulations on the use of new and existing fungicides are becoming more and more stringent. For example, depending on the commodity, the postharvest use of fungicides is completely prohibited in some European countries or limited to just a few registered chemicals. Even if their use is allowed to some limited degree, many large supermarket chains and wholesale fruit suppliers are setting their own standards for chemical residues and the number of active ingredients allowed to be present on harvested commodities. As detailed by Sanzani et al. (2016), safety concerns about mycotoxins and foodborne pathogens also increase the need to find viable alternatives. Additionally, potential restrictions on the use of some fungicides used before harvest could also result in increased levels of inoculum of postharvest pathogens and the number of latent infections that are established.

The search to identify alternative approaches to postharvest disease management must be viewed in relation to a complex regulatory environment, the need to address disease problems in a wide array of commodities and conditions, industry and consumer acceptance, and last but not least, commercial viability. In order for companies to invest in new technologies, they must be able to clearly see both the value of a product and the financial return on their investment. The present review attempts to highlight how the search for alternative postharvest disease management technologies has been a journey from simplicity to complexity. This simplicity began with the idea of using microbial antagonists as postharvest biocontrol agents, and then grew in complexity as other methods were explored to either enhance the use of microbial antagonists or to be used as stand-alone methods. This complexity was eventually encompassed by an expanded defini- tion of biological control and this review is meant to serve as an introduction to the other timely contributions presented in this Special Issue that reflect the complexity and diversity of alternative approaches to postharvest disease management.

## A simple idea-the birth of postharvest biocontrol and the pursuit of alternative strategies

The use of biocontrol agents, natural compounds, and assorted physical treatments as alternatives to the use of synthetic fungicides was a relatively obscure topic of research until the mid-1980's. For instance, prior to late 1980's, one could count on the fingers of one hand the number of publications that investigated the use of microbial antagonists for managing postharvest diseases (Tronsmo and Dennis, 1977; Wilson and Pusey, 1985). The search for alternative strategies that were commercially viable was launched into the mainstream by several factors, but primarily by a report by US National Research Council (NRC) (1987) which stated, "As a class, fungicides present special difficulties because nine oncogenic compounds account for about 90% of all fungicide sales." The report also indicated that fungicides represented 60% of the oncogenic risk among all pesticides. This created a great concern that loss of these compounds, either from being banned by regulatory agencies or an unwillingness of manufacturers to renew their registrations, would have a severe economic impact on the production of several crops. Health concerns were further exacerbated by a later report by the NRC (1993) which indicated the increased vulnerability of children to exposure to synthetic pesticides. Concern about the widespread development of fungicide resistance also helped to fuel the search for alternative methods of disease control.

The studies by the NRC resulted in a negative perception of synthetic, chemical pesticides and served as the basis for limiting the number of registered active ingredients, by eliminating those with negative effects on human and animal health, both in the United States (Food Quality Protection Act) and in the European Union (Regulation 1107/2009). Several of the discontinued fungicides (e.g. benomyl, captan, maneb, thiophanate methyl, and chlorothalonil) have been replaced by new less toxic fungicides. Nevertheless, the NRC report is still cited in many of the recent reports and reviews published on alternative postharvest disease management practices, as one of the major factors driving this research effort. There is still a great concern on the part of the public, however, to further restrict the use of synthetic chemicals, and their residues. The ability to preserve the quality of harvested produce throughout the various aspects of the supply chain (storage, shipment, shelf-life, etc.) has also been recently recognized as an important tool in providing an adequate food supply to an ever increasing world population (Wisniewski et al., 2014). Farmers, industry, regulatory agencies, the research community, and consumers all have a vested interest in finding safe, effective, and economically-viable approaches to managing and reducing postharvest losses of harvested commodities.

The use of various microbes (yeast, yeast-like fungi, and bacteria), isolated from plant, fruit, and soil, as antagonists (biocontrol agents) to manage postharvest diseases came from the observation that administering high concentrations (in the range of $1 \times 10^6$ to $1 \times 10^8$ CFUs/ml) of some microbes to wounded fruit tissue, followed by inoculation with pathogen spores ($1 \times 10^3$ to $1 \times 10^4$ spores/ml, or higher), prevented infections from being established when the fruit was stored at either room or low temperatures. Wilson and Pusey (1985) highlighted the potential of this technology and this field of research has grown exponentially in the past 20–30 years. The literature on this topic has grown from a handful of publications each year to literally hundreds each year. Numerous reviews on this subject have been and continue to be published (Wilson and Wisniewski, 1989; Wisniewski and Wilson, 1992; Ippolito and Nigro, 2000; Janisiewicz and Korsten, 2002; Spadaro and Gullino, 2004; Droby et al., 2009; Sharma et al., 2009; Jijakli, 2011; Nunes, 2012; Liu et al., 2013; Sui et al., 2015; Spadaro and Droby, 2016). New antagonists, new ways to use the antagonists, and new ways to integrate their use with other alternatives approaches are continually being published. Despite hundreds of reports documenting potential, commercially-viable, antagonists, the widespread use of a single product has not been achieved. Several products initially reached the market but were later discontinued, while others have achieved success in limited niche markets (Table 2). This has been due to several factors (Droby et al., 2009; Droby et al., 2016), including inconsistent performance, lack of industry acceptance, cost relative to synthetic fungicides, registration hurdles, and formulation problems. What started as a simple idea, using microbial antagonists to manage postharvest diseases, slowly evolved in complexity, as attempts to overcome these problems have been pursued. This complexity grew out of the initial idea of using microbial antagonists and finding ways to improve their efficacy. This effort eventually led to using other approaches as both stand-alone approaches in their own right or in combination with more traditional biocontrol approaches. The postharvest environment, including packing-house treatments, storage, shipping, and all other aspects of the supply chain are now being viewed as a system requiring a broad, holistic view to address a wide range of quality issues. Truly, our basic understanding of and practical experience in developing alternative postharvest strategies has grown from simplicity to complexity.

## Expanding the alternatives for postharvest disease management

Soon after the potential of using microbial antagonists as postharvest biocontrol agents was recognized, methods to enhance their performance and reliability were explored. Since some of the early yeast antagonists were known to have been isolated from high-salt food environments (soy sauce, pickle juice, etc.), the use of salts as an additive to biocontrol protocols was explored (McLaughlin et al., 1990; Droby et al., 1997; Smilanick et al., 1999). This research focused mainly on the use of calcium and sodium salts, primarily $CaCl_2$ and $NaHCO_3$ (Conway et al., 2004; Ippolito et al., 2005; Janisiewicz et al., 2008b). Other methods that were explored included the use of chitosan (El- Ghaouth et al., 2000; Meng et al., 2010; Romanazzi et al., 2016a), glucose (Sui and Liu, 2014), the integration of UV-C with antagonists (Stevens et al., 1997), combining the use of antagonists with heat treatments (Conway et al., 2004; Liu et al., 2011), organic salts and surfactants (Nigro et al., 2006), modified atmosphere storage (Spotts et al., 2002; Karabulut and Baykal, 2004), and ethylene inhibitors (Osman et al., 2011). The use of various physical treatments, natural plant and animal products and the identification and potential of plant and fungal derived volatile organic compounds (VOCs) are detailed in this issue by Usall et al. (2016), Palou et al. (2016) and Mari et al. (2016), respectively. The search for stress resistant antagonists was also pursued (Sui et al., 2015). The importance of sanitation in reducing inoculum levels has also been recognized as both a standalone practice and integrated with other alternative management strategies (Feliziani et al., 2016).

Two new concepts were gradually incorporated into the development of alternative methods of postharvest disease management. One was an expanded definition of biological control conceived by Dr. Charles Wilson (discussed in Wisniewski et al., 2007; Droby et al., 2009) in which biological control is defined as “the management of a plant disease by a biological process or the product of a biological process." This new definition, incorporated the new approaches and ideas that were being explored for developing alternative approaches to postharvest disease management. In addition to the use of antagonists, the exploration of innate and induced resistance and the use of natural antimicrobials (including VOCs) were also seen as an alternative biological approach to disease management. Romanazzi et al. (2016b) presents a review of induced resistance and Gonzalez-Candelas and Tian (2016) review the molecular aspects of virulence and resistance.

The second concept that has evolved within the search for alternative approaches to postharvest disease control is the idea of a multiple decrement approach (Smilanick, *pers. comm.*). The foundation of this principle is that the prevention of disease is brought about by the use of several approaches that each reduce the percentage of decay by a specific amount. The various approaches act together additively or synergistically to bring about commercial levels (97–99%) of disease control (Fig. 1). This multi-step approach may include: Action 1 - Reduce inoculum levels through sanitation and or careful harvesting and handling; Action 2 - Exposure to a wet or dry heat treatment, Action 3 - Application of a microbial antagonist, and Action 4 - use of modified or controlled atmosphere storage and/or packaging.

In the food industry the multiple hurdle approach is used to manage foodborne pathogens. In practice, no single intervention can completely eliminate pathogenic bacteria from a food product (Leistner, 2000). To ensure the product is safe and presents the lowest risk possible, a robust multiple-hurdle approach is implemented. Each step in the handling and processing of food material provides an opportunity to control bacteria, prevent cross-contamination, and prevent the spread of bacterial contamination to downstream processes. This approach is based on the use of intervention technologies at critical points throughout the harvesting, handling, storage, shipping, and marketing process. Perhaps the model used to deal with foodborne pathogens should also be used to develop effective strategies for preventing postharvest diseases. It seems that integrating approaches, from the field to the supermarket, will be the key to success in developing safe, effective, and reliable alternatives.

## Alternative products: from the frying pan into the fire

In their seminal publication, Wilson and Wisniewski (1989) outlined the criteria of an ideal antagonist. While most of the designated criteria mentioned in that report are still relevant, they also made a case for favoring yeast over bacterial antagonists as biocontrol agents. This was based on the perceived premise that consumers would be more comfortable with food that had been treated with yeast (used in baking and making beer) than with bacteria (often associated with foodborne diseases), and potential problems with the registration of bacterial antagonists producing antibiotics. While in theory this may have been true, and is actually reflected in the number of reports using antagonistic yeasts rather than bacteria, in a practical and historical sense it did not turn out to be the case. In fact one of the first and longest available postharvest biocontrol products, BioSave (JetHarvest Solutions, Longwood, Florida, USA), is based on the bacterium *Pseudomonas syringae* (Janisiewicz and Jeffers, 1997). Other successful pre- and postharvest biocontrol products are also based on bacteria, primarily *Bacillus subtilis* (known to produce the antibiotic, iturin) and its fermentation products. So the challenge of developing a successful yeast-based biocontrol product still exists. While the product Aspire (Ecogen, Inc.), based on the yeast *Candida oleophila*, was developed at the same time as BioSave, poor marketing and company management resulted in its disappearance from the market place. Other postharvest biocontrol products have moved toward commercial status but remain in limbo due to regulatory problems and lack of company support.

Droby et al. (2009) in their twenty-year review of postharvest biological control research discussed in detail the major obstacles facing the commercialization of postharvest biocontrol products. While they focused on the use of microbial antagonists, similar obstacles exist for any new technology. An essential aspect of commercial development is for the technology to be protected by patents to ensure that a company can capitalize on their investment. Demonstrating the originality of new technology that will withstand the “prior art and obviousness test” to which it will be subjected to during the patent review process is a difficult challenge. Perhaps the greatest obstacle is consistent and reliable performance under a wide array of conditions (different packing lines, different inoculum levels, use of other technologies used to maintain quality). Whether or not a package of treatments specifically designed for each individual crop is an acceptable commercial model remains to be seen. The costs associated with product development, marketing, and industry acceptance are the other factors that have limited the adoption of alternative technologies. There is a wealth of information on alternative approaches to postharvest diseases management, yet none of these approaches have been implanted on a large scale, although the use of heated solutions of sodium carbonate/sodium bicarbonate have been in widespread use in the citrus industry in California since the early 1930's (Barger, 1928). There is a critical need to find a way to bridge the gap between research and industry so that these alternatives can become commercial successes. These are the challenges and opportunities facing the development of alternative approaches to postharvest disease control.

## The Big Bang: moving from simplicity to complexity

The past twenty years has seen a revolution in systems biology fostered by the advances in omic technologies (genomics, transcriptomics, metabolomics, proteomics, and metagenomics). Undoubtedly, these tools are greatly enhancing our understanding of the interactions between microbial antagonists, host tissues, pathogens, biotic and abiotic elicitors of defense mechanisms and the environment. In particular, elucidating the role of reactive oxygen species and oxidative stress in biocontrol systems has greatly enhanced our understanding of what happens when antagonists are applied to the wound site in the presence and absence of pathogens (Macarisin et al., 2010). The induction of host defense responses by several alternative approaches, including antagonists (Ippolito et al., 2000; Hershkovitz et al., 2012), natural compounds (e.g. chitosan) (El-Ghaouth et al., 2000; Feliziani et al., 2015), and heat (Spadoni et al., 2014, 2015) have all been reported. A greater understanding of the role of abiotic stress in biocontrol systems has also been developed (Sui et al., 2015).

Massive sequencing of polymerase chain reaction (PCR) amplicons from specific barcode genes (amplicon metagenomics or metabarcoding) has proved to be a powerful culture-indepen- dent technique for investigating microbial diversity and for determining the relative quantity of community members in environmental samples (Lindahl et al., 2013). The identification and quantification of endophytic and epiphytic microflora present in and on plants may provide information that can facilitate an understanding of the complex interactions that take place between plants and resident fungal microflora, including pathogenic and beneficial species (Schena et al., 2003; Ottesen et al., 2013; Pinto et al., 2014; Abdelfattah et al., 2015). Furthermore, these techniques enable an in-depth investigation of the effect of conventional and alternative control methods, including the application of biocontrol agents, on the composition and diversity of microbial communities (Sylla et al., 2013).

More recently, Janisiewicz et al. (2008a) and Jurick et al. (2011) have identified resistance to *Penicillium expansum* and *Colletotrichum* sp. in a number of accessions of wild apple species, including *Malus sieversii*. Use of a mapping population (‘Royal Gala’ X *M. sieversii* PI 613981), that segregates for blue mold resistance, has enabled the identification of a quantitative trait locus (QTL) on chromosome 3 of apple (Norelli et al., 2014; Wisniewski et al., 2016, in press). Development of a DNA test for this genetic locus will allow apple breeders to screen for blue mold resistance in seedlings and juvenile trees prior to fruiting. In stark contrast to many other crops, few fruit cultivars with both postharvest disease resistance and superior horticultural quality are commercially available. Numerous challenges have severely limited breeders’ ability to deliver cultivars with both attributes. Resistance to many disease threats is present in crop wild relatives and these donor parents usually have small fruit and numerous other highly undesirable horticultural attributes such as bitterness, astringency, and poor keeping qualities. In most cases, little is known about the nature and inheritance of the disease resistance. Using traditional backcrossing strategies, many generations are required to regain sufficient horticultural quality, a process that can require decades for most tree fruit crops and in all cases requires extensive and expensive field testing.

DNA-informed breeding for disease resistance and horticultural quality is expected to overcome the traditional breeding impasse of past decades. Firstly, DNA-informed breeding can improve breeding efficiency by selecting parents known to carry critical alleles, by accurately designing crosses to achieve desired genetic combinations that avoid inefficient or useless crosses and by identifying inferior offspring prior to field planting. Additionally, marker assisted breeding (MAB) allows the efficient pyramiding of multiple sources of resistance which could enhance the durability of resistance. Identifying individuals with pyramided disease resistant genes is often not even possible without DNA markers linked to the resistance because it is impossible to select on phenotype alone for the presence of a second resistance gene. Finally, because the presence or absence of a DNA locus is not affected by environmental conditions or host physiology, DNA tests can be more reliable than traditional phenotypic methods of selection. For example, the infection of apple fruit by *P. expansum* is affected by fruit ripeness (Villanova et al., 2012), yet the progeny of any specific cross is likely to segregate for harvest date, fruit firmness and starch content at maturity making the phenotypic evaluation of resistance both difficult and prone to variation. In contrast, a DNA test which can be conducted using leaf tissue or any other source of DNA is not affected by fruit ripening or other host physiological effects.

As discussed above and by Droby et al. (2016), the field of metagenomics provides the opportunity to investigate communities of microbes that exist on plant surfaces, how they interact, and how they change over time. In the future, this knowledge will allow a systems approach to disease control and perhaps lead to the ability to create synthetic communities of organisms for enhanced disease management. Essential to all the-omic technologies that have been developed is the ability to analyze and mine large data sets (millions to hundreds of millions of data from different sources). Every biologist has come to appreciate the value and necessity of a good bioinformatics pipeline.

## Conclusions

It has been often stated that we have moved from an age of chemistry to an age of biology. The ease of sequencing genomes and obtaining related genotypic, transcriptomic, proteomic, and metabolomic information is leading to the development of new commercial technologies where problems are solved “biological- ly.” In regards to postharvest disease control, truly we have moved from simplicity to complexity in our understanding of how we can manage postharvest diseases in a cost-effective, and reliable manner and how various alternative technologies (antagonists, natural compounds, physical treatments) impact the host and the community of microorganisms that we are attempting to manage and regulate. Plant pathologists developing alternative technologies are slowly moving away from the “silver bullet” concept where a single intervention can be used to control a disease to viewing plant disease as a process where multiple interventions may be required at different points in the disease process. Over the past thirty years, alternatives have moved from the simple idea of applying high concentrations of biocontrol agents to a harvested commodity, to using a wide array of other approaches, and integrating them together into a systems approach based on the multiple decrement or multiple hurdle concept. It has been a long journey from simplicity to complexity, and as Shakespeare reveals in the quote at the beginning of this contribution, thereby hangs a tale.

## Acknowledgement

The current review was not designed to be comprehensive and inclusive of the many

hundreds of reports that have been published on this topic. Rather, it was designed to provide a ‘historical’ view of how the field has developed over the past thirty years and the ideas and concepts that helped to shape it. We would like to extend our gratitude to all those researchers, mentioned and unmentioned, who have diligently worked to find and develop safe and effective alternatives for the management of postharvest diseases. In many traditions, the earth was originally perceived as a “Garden of Eden.” As the activities of humans, both in industry and population growth, begin to represent a real challenge to the health and sustainability of the planet, let us hope that science and ethical conviction can provide a safe and bountiful harvest for all the people of future generations. A portion of the research described in this review was partially funded by a grant (US-4774- 14C) from the U.S. Israel Binational Agricultural Research and Development Fund.

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**Table 1.** Alternative management technologies for postharvest disease control.[a]

| Treatment | Fruit host | Target pathogen | Reference |
|---|---|---|---|
| **Biological Control** | | | |
| Yeast antagonist | | | |
| *Candida oleophila* | Apple | *Penicillium expansum*, *Botrytis cinerea* | Mercier and Wilson (1995), Liu et al. (2012b) |
| *Candida sake* | Apple, Grape | *P. expansum*, *B. cinerea* | Morales et al. (2008), Cañamás et al. (2011) |
| *Metschnikowia fructicola* | Grapefruit,<br>Apple | *Penicillium digitatum*,<br>*P. expansum* | Hershkovitz et al. (2013),<br>Liu et al. (2011) |
| *Cryptococcus albidus* | Apple | *P. expansum*, *B. cinerea* | Fan and Tian (2001) |
| *Cryptococcus laurentii* | Strawberry | *B. cinerea* | Wei et al. (2014) |
| *Pichia anomala* | Banana | *Colletotrichum musae*, *Fusarium moniliforme* | Lassois et al. (2008) |
| *Pichia guilliermondii* | Apple, Kiwifruit | *B. cinerea* | Wisniewski et al. (1991), Sui and Liu (2014) |
| *Aureobasidium pullulans* (yeast-like fungus) | Peach, Apple, Plum | *Monilinia laxa*, *P. expansum*, *B. cinerea*, *Colletotrichum acutatum* | Zhang et al. (2010), Mari et al. (2012) |
| Bacterial antagonist | | | |
| *Pantoea agglomerans* | Apple | *P. expansum* | Morales et al. (2008) |
| *Bacillus subtilis* | Tomato | *Rhizopus stolonifer* | Ma et al. (2015) |
| *Pseudomonas syringae* | Banana | *Fusarium pallidoroseum*, *F. proliferatum* | Williamson et al. (2008) |
| *Bacillus amyloliquefaciens* | Citrus | *Penicillium italicum*, *P. digitatum* | Hao et al. (2011) |
| **Physical Treatment** | | | |
| Heat | | | |
| Hot water dipping | Peach<br>Apple | *Monilia fructicola*, *M. laxa*,<br>*P. expansum* | Liu et al. (2012a), Spadoni et al. (2014)<br>Spadoni et al. (2015) |
| Hot water rinsing | Apple | *Neofabraea alba* | Maxin et al. (2012) |
| Hot water brushing | Grapefruit | *P. digitatum* | Pavoncello et al. (2001) |
| Hot air treatment | Sweet cherry | *P. expansum* | Wang et al. (2015) |
| Vapor heat treatment | Table grape | *B. cinerea* | Lydakis and Aked (2003) |
| **UV-C** | | | |
| | Tomato | *Rhizopus stolonifer*, *B. cinerea* | Steven et al. (2004), Charles et al. (2009) |
| | Papaya | *Colletotrichum gloeosporioides* | Cia et al. (2007) |
| | Melon | *Fusarium oxysporum*, *Alternaria alternata* | Huang et al. (2015) |
| **Modified Atmosphere** | | | |
| | Sweet cherry | *M. fructicola* | Spotts et al. (2002) |
| | Peach | *P. expansum*, *B. cinerea* | Karabulut and Baykal (2004) |
| | Apple | *P. expansum* | Conway et al. (2007), Janisiewicz et al. (2008) |
| **Natural Compounds** | | | |
| Chitosan | | | |
| | Tomato | *P. expansum*, *B. cinerea* | Liu et al. (2007) |
| | Table grape | *B. cinerea* | Romanazzi et al. (2007) |
| | Strawberry | *B. cinerea* | Feliziani et al. (2015) |
| Oligochitosan | | | |
| | Jujube | *M. fructicola*, *A. alternata* | Yan et al. (2012) |
| | Apple | *M. fructicola* | Yang et al. (2012) |
| | Orange | *C. gloeosporioides* | Deng et al. (2015) |
| **Essential oil** | | | |
| Vervain oil | Peach | *Monilinia fructigena*, *M. laxa*, *M. fructicola* | Elshafie et al. (2015) |
| Thyme oil | Avocado | *C. gloeosporioides* | Sellamuthu et al. (2013) |

| | | | |
|---|---|---|---|
| Lemongrass oil | Peach | *R. stolonifer*, *B. cinerea* | Arrebola et al. (2010) |
| Tea tree oil | Strawberry | *B. cinerea* | Shao et al. (2013) |
| Oregano oil | Table grape | *Aspergillus flavus*, *Aspergillus niger* | de Sousa et al. (2010) |

[a] There are numerous published reports on these alternative strategies. An attempt was made to list representative references, and apologize to investigators whose specific results could not be cited due to space limitations.

**Table 2 -** Alternative Technologies that have been developed into products.

| Product | Active Ingredient | Country and/or Company | Fruit | Target Pathogens | In Use |
|---|---|---|---|---|---|
| Aspire | *Candida oleophila* | Ecogen<br>USA | Pome Fruit, Citrus, Strawberry, Stone Fruit | *Botrytis, Penicillium, Monilinia* | No |
| YieldPlus | *Cryptococcus albidus* | Lallemand<br>South Africa | Pome Fruit, Citrus | *Botrytis, Penicillim, Mucor* | No |
| Candifruit | *Candida sake* | IRTA/Sipcam-Inagra<br>Spain | Pome Fruit | *Penicillium, Botrytis, Rhizopus* | No |
| Biosave | *Pseudomonas syringae* | Jet Harvest<br>USA | Pome Fruit, Citrus, Strawberry, Cherry, Potato | *Penicillium, Botrytis, Mucor* | Yes |
| Avogreen | *Bacillus subtilis* | South Africa | Avocado | *Cercospora, Colletotrichum* | No |
| Nexy | *Candida oleophila* | Leasafree<br>Belgium | Pome Fruit | *Botrytis, Penicillium* | Yes |
| BoniProtect | *Aureobasisium pullulans* | Austria | Pome Fruit | *Penicillium, Botrytis, Monilinia* | Yes |
| Pantovital | *Pantoea agglomerans* | IRTA/Sipcam-Inagra<br>Spain | Citrus, Pome Fruit | *Penicillium, Botrytis, Monilinia* | No |
| Shemer | *Metschnikowia fructicola* | Bayer/Koppert<br>The Netherlands | Table Grape, Pome Fruit, Strawberry, Stone Fruit, Sweet Potato | *Botrytis, Penicillium, Rhizopus, Aspergillus* | Yes |

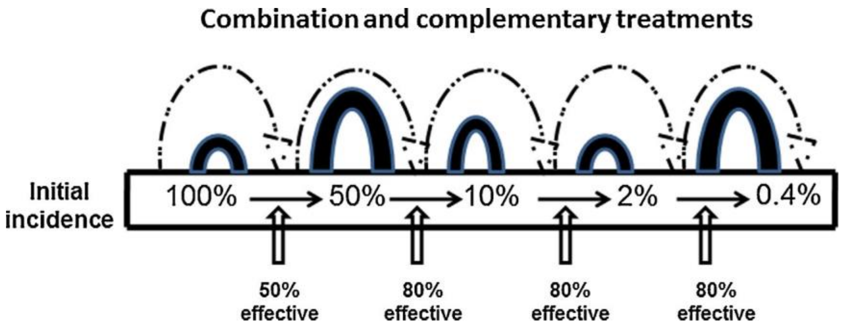

**Fig. 1.** The multiple decrement approach to managing postharvest decay. Various approaches act together additively or synergistically to bring about commercial levels (97– 99%) of disease control. This multi-step approach may include the use of one or more of the approaches discussed in this Special Issue. For example, Action 1—reduce inoculum levels through sanitation and or careful harvesting and handling; Action 2—exposure to a wet or dry heat treatment, Action 3—application of a microbial antagonist, and Action 4—use of modified or controlled atmosphere storage and/or packaging.