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Review

Climate Changes and Food Quality: The Potential of Microbial Activities as Mitigating Strategies in the Wine Sector

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Received: 6 September 2019; Accepted: 19 September 2019; Published: 23 September 2019

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Abstract: Climate change threatens food systems, with huge repercussions on food security and on the safety and quality of final products. We reviewed the potential of food microbiology as a source of biotechnological solutions to design climate-smart food systems, using wine as a model productive sector. Climate change entails considerable problems for the sustainability of oenology in several geographical regions, also placing at risk the wine typicity. The main weaknesses identified are: (i) The increased undesired microbial proliferation; (ii) the improved sugars and, consequently, ethanol content; (iii) the reduced acidity and increased pH; (iv) the imbalanced perceived sensory properties (e.g., colour, flavour); and (v) the intensified safety issues (e.g., mycotoxins, biogenic amines). In this paper, we offer an overview of the potential microbial-based strategies suitable to cope with the five challenges listed above. In terms of microbial diversity, our principal focus was on microorganisms isolated from grapes/musts/wines and on microbes belonging to the main categories with a recognized positive role in oenological processes, namely *Saccharomyces* spp. (e.g., *Saccharomyces cerevisiae*), non-*Saccharomyces* yeasts (e.g., *Metschnikowia pulcherrima*, *Torulaspora delbrueckii*, *Lachancea thermotolerans*, and *Starmerella bacillaris*), and malolactic bacteria (e.g., *Oenococcus oeni*, *Lactobacillus plantarum*).

Keywords: climate change; food quality; viticulture; wine; fermentation; yeast; *Saccharomyces*; non-*Saccharomyces*; alcoholic fermentation; lactic acid bacteria; malolactic fermentation

1. Introduction

"Climate change threatens our ability to ensure global food security, eradicate poverty and achieve sustainable development. Greenhouse gas (GHG) emissions from human activity and livestock are a significant driver of climate change, trapping heat in the earth's atmosphere and triggering global warming. Climate change has both direct and indirect effects on agricultural productivity including changing rainfall patterns, drought, flooding and the geographical redistribution of pests and diseases. FAO is supporting countries to both mitigate and adapt to the effects of climate change through a wide range of research based and practical programmes and projects, as an integral part of the 2030 agenda and the Sustainable Development Goals." http://www.fao.org/climate-change/en/.

It is clear how widespread and complex the impacts of climate change phenomena associated with global warming on food systems are [1–5]. We can disentangle these extensive and multifaceted influences in different (often interdependent) components, such as agricultural, livestock and fishery yields, food prices, effectiveness of delivery, global food quality, and, a crucial facet of global quality, food safety [6]. Great attention has been placed to many aspects related to food security (e.g., yields reduction, prices rises). Instead, marginal interest has been given to quality issues, including, among others, palatability, hygienic properties, nutritional contributes, and functional contributes. For fermented foods and beverages, microbes' activity associated with the matrices is susceptible to affect all the main aspects contributing to the final product quality [7,8]. Mitigation and adaptation strategies for the effects of climate change belong to different disciplines, such as agricultural sciences, plant and animal biology and breeding, food technology, and food microbiology. In this mini-review article, we use wine as a model matrix to describe the impact of climate changes on the quality of fermented matrices, examining the potential of protechnological microbes as agents capable to 'mitigate' the negative features of this evolving climatic influence.

Within the macro-category of fermented products, wine belongs to the group of fermented alcoholic beverages [7]. Yeasts are responsible for alcoholic fermentation (AF) and more generally, for biochemical changes linked to the chemical transformation of must obtained from grapevine crushing in wine [9–11]. Among oenological yeasts, the following categories can be found: (i) Yeast belonging to the *Saccharomyces* genera, and particularly to the *Saccharomyces cerevisiae* species, which are mainly responsible for alcoholic fermentation in wine [10–12]; and (ii) the heterogeneous category of the so-called non-*Saccharomyces* yeasts [10,11,13]. Within this complex category, we can find both protechnological species/strains [13,14] and spoilage organisms [15,16]. Non-*Saccharomyces* of interest for their oenological aptitude, other than contributing to alcoholic fermentation, can be helpful to solve specific technological/oenological issues (e.g., reduction of volatile acidity) [13,17], to modulate wine aroma [17–19], and/or to exert biocontrol activity against undesired microbes [20–22]. Together with the eukaryotic contribution to wine quality, we have to mention malolactic bacteria to encompass all microbes that positively modulate wine chemistry. Malolactic bacteria and lactic acid bacteria (LAB) are capable of decarboxylating malic in lactic acid, and are responsible for the so-called malolactic fermentation (MLF), a process associated with positive changes in palatability, increased aromatic complexity, and enhanced microbial stability [23].

2. Wine Quality and Climate Change

Climate change affects, to different extents, wine production and quality. About 10 years ago, Mira de Orduña provided an extensive review of the 'climate change-associated effects on grape and wine quality and production' [24]. The review followed a cause-and-effect ratio analysis, and pointed out the effects on viticulture and the corresponding consequences on winemaking. Adopting this point of view, we can examine the main effects of climate change on viticulture and oenology (Table 1).

Table 1. A list of the effects of climate change on viticulture and enology. Often, oenological effects are a consequence of viticultural effects.

Viticultural Effects	Oenological Effects
Harvest dates	Harvest conditions and fruit quality
Grape maturation (effect of temperature, of carbon dioxide and of radiation)	Effects of high sugar and alcohol concentrations
Indirect effects of climate change	Microbial and sensory effects of lower acidities and increased potassium and pH levels
Effects on vine pests	Climate change associated effects on wine chemistry
Effect on root systems	Effect on oak

Modified from Mira de de Orduña [24].

Harvesting is in a double relationship with climate trends; on the one side, harvesting is a function of the seasonal climate, on the other, it provides a criterion to classify different grapevine varieties depending on their relationship to the climate. In general, data from different grapevine production areas offer a picture of prior fruit maturation patterns, with a consequential shift forward of the harvesting time [24]. Considering the different grapevine varieties, recent evidence on early wine grape harvests in France indicates that climate change has profoundly transformed the climatic drivers of the plant, with possible repercussions for viticulture management and wine quality [25,26]. If we consider the general influence of temperature increases, not only on a given phenological phase (i.e., fruit maturity), we have to report an increase in sugar contents, decreased concentration of organic acids/total acidity, and improved potassium content [24,27]. Moving from primary to secondary metabolites, the effort to summarize specific trends becomes more complex, giving that more variables act in the system that are susceptible to influencing the pathways associated with metabolites' biosynthesis: Temperature, carbon dioxide, and radiation [24]. In general, climate change has led to significant modulations in the accumulation of heterogeneous classes of polyphenols and volatile organic compounds [24,28]. In addition to the direct effect, we have to consider the indirect effects, such as enhanced salinity and increased probability of wild bushfires [24]. Present evidence also suggests that climate change can influence the proliferation of certain viticultural pathogens, introducing new insight into pest management in the field [24]. We must also consider the direct effects on the root system imputable to the response of the plant to abiotic heat stress. Finally, the effects on the development and quality of oak, the main wood utilized for wine aging, caused by modifications of carbon dioxide levels and weather patterns have been considered [24].

Shifting from the viticultural to the oenological aspects, we may list the main consequences on the wine quality of the highlighted effects on the raw material. The shift of the harvest date and the impact on grape maturation can intensify oxidative phenomena (e.g., oxidation of specific volatiles) and microbial growth (e.g., increased microbial spoilage proliferation, enhanced risks of starvation during the fermentative process, and increased the content of toxic compounds released by undesired microorganisms, such as mycotoxins) [24,25,27]. The immediate oenological consequence of an increased sugar content is an improved concentration of ethanol in the final product. This phenomenon implies a higher likelihood of stuck/sluggish during the alcoholic fermentation, sharpened microbial stress response, modulation of sensory perception (prominent alcohol sense and a reduced passage of volatiles in the wine headspace, increasing the perception of astringency, masking the perception of esters), and lowered social acceptance of wines, due to the recognized toxic effect of ethylic alcohol (without considering the impact on caloric intake) [28]. Increased pH implies the following: (i) An improved risk of undesired microbial proliferation, from the first fermentative steps (e.g., lactic acid bacteria, spoilage yeasts) up to the aging/finished wines (e.g., *Dekkera/Brettanomyces* yeasts); and (ii) changes in the wine colour, taste, and aroma [28]. Modifications in the wine colour, taste, and aroma can also be addressed by modulation of the compound directly responsible for these perceptions. The phenomena associated with climate change seem to lessen anthocyanins and enhance the proanthocyanidins content, contributing to a reduction of the 'colour potential' and to pronounced astringency [27,28]. In terms of the concern regarding aroma compounds, even if it is difficult to depict clear trends, it is possible to point out some patterns [29,30]. First, it is worth remembering that notes of "green pepper, herbaceous, blackcurrant, blackberry, figs, or prunes are strongly linked with the maturity of the grapes" [31]. The 'cooked' aroma generally increases with temperature. Contrastingly, pyrazine accumulation follows an opposite change (responsible for 'veggie, herbaceous notes') [27,29,32]. The same was found for rotundone contents in grapes (responsible for the peppery aroma) [29]; whereas contrasting results were reported for the terpenol family [29].

It is possible to speculate that the present literature presents findings that are not always harmonic and that it remains difficult to combine direct and indirect effects, both positive and negative. To this purpose, Drappier et al. [28] observed that the remarkably hot 2003 season in Europe offered the opportunity to mimic and test in vivo the climatic condition expected by the conclusion of this century, demonstrating the potential of climate change in clouding wine typicity. With this concern, the authors reported, in light of the recent experimental investigations, the sensory features associated with the different viticultural climates: Enhanced alcohol perception, reduced acidity sense, imbalanced colour development, and perceived aroma [28]. These are sensory defects that are generally coherent with the indications reported in the scientific literature.

3. The Potential of Microbial Activities as Mitigating Technologies

When facing emerging challenges, humans explore different routes in order to find innovative solutions suitable to ensuring the sustainability of resources and productions. This is also true for the problems in food systems triggered by climate change. For example, in the wine sector, the scientific and professional communities have proposed numerous possible approaches susceptible to developing a climate-smart wine system. These potential solutions range from the agronomic and viticultural fields up to applications in the technology and biotechnology branches, with different potentials in terms of performances and temporal horizons. Among other factors, microorganisms can also exert activities to mitigate product depreciation due to climate change. Here, we propose an overview of potential microbial-based strategies able to concretize mitigating biotechnologies, declined in five categories corresponding to the main safety/quality aspects affected by climate changes in oenology.

3.1. Microbial Solution for the Biocontrol of Spoilage Microorganisms in Wine

The main spoilage microbes in enology belong to the yeast genera Brettanomyces (e.g., *B. bruxellensis*), Candida (e.g., *C. stellata*), Hanseniaspora (e.g., *H. vineae*), Pichia (e.g., *P. anomala*, *P. membranifaciens*), and Zygosaccharomyces (e.g., *Z. bailii*, *Z. rouxii*); and to the bacterial genera Lactobacillus (e.g., *L. hilgardii*), Leuconostoc (e.g., *L. mesenteroides*), Pediococcus (e.g., *P. damnosus*, *P. pentosaceus*), Acetobacter (e.g., *A. aceti*, *A. pasteurianus*), or Gluconobacter (e.g., *G. oxydans*) [33,34]. The increasing incidence of these spoilage microbes could be responsible for considerable economic losses in this sector. In Table 2, we propose an exemplified list of microbial applications potentially suitable to ensuring the control of microbial spoilage.

Table 2. A list of studies that propose microbial-based solutions that can have potential applications in mitigating the development of spoilage microorganisms in wine.

Microorganisms Involved	Microbial-Based Mitigating Strategies	References
Lactococcus lactis (as producer of lacticin 3147)	Use of lacticin 3147 for the biocontrol of lactic acid bacteria in oenology	[35]
Metschnikowia pulcherrima	Biocontrol of spoilage yeasts via iron depletion	[36]
Saccharomyces cerevisiae	Killer activity as biocontrol agents to avoid or reduce wine spoilage	[37]
Enterococcus faecium	Enterocin heat stable, with broad pH range and bactericidal effects	[38]
Pichia membranifaciens	Killer toxin active against spoilage yeast in wine	[39]
Torulaspora delbrueckii	Use as a bio-protective agent alternative to sulphites in winemaking	[40]
Wickerhamomyces anomalus and *Metschnikowia pulcherrima*	Biocontrol activity against spoilage yeasts in winemaking	[22]
Saccharomyces cerevisiae, *Candida zemplinina*, *Hanseniaspora uvarum*, *Hanseniaspora guilliermondii*, *Torulaspora delbrueckii*, *Metschnikowia pulcherrima*	Use of co-inoculation of autochthonous yeasts and bacteria in order to control *Brettanomyces bruxellensis* in wine	[21]

Biocontrol provides alternatives to chemical preservatives, such as SO_2, which is associated with adverse reactions in humans [40]. We recognize two different categories of microbial-based solutions: The case when a product of microbial metabolism is added as biopreservatives in the wine chain [34,35,38] or the option to add to the matrix the microorganism itself as a starter/protective culture [20,37,40]. Considering the molecular basis responsible for the antagonistic microbial phenotypes, we highlight two main categories, competition for nutrients and the production of molecules with antimicrobial activities. Concerning the last class, yeasts' killer toxins and bacteriocins are the main reservoirs of this competitive arsenal developed by specific yeasts and bacteria that find potential applications in wine [41].

3.2. Microbial-Based Solutions to Reduce Ethanol Content

High ethanol concentration may reduce the complexity of wine by suppressing the aroma intensity, but also by exalting the perception of 'hotness' and 'bitterness'. Moreover, health considerations combined with market demand make the wine industry actively seek ways to facilitate the production of wines with lower alcohol concentration [42]. Among the possible approaches, microbial strategies present an attractive opportunity to decrease ethanol levels while preserving the quality and aromatic integrity of the wine (Table 3).

Table 3. A list of studies that propose microbial-based solutions that can have potential applications in mitigating an increased ethanol concentration.

Microorganisms Involved	Microbial-Based Mitigating Strategies	References
Saccharomyces cerevisiae	Selection of less ethanol producer yeasts	[43,44]
Saccharomyces cerevisiae	Adaptive evolution to conditions where glycerol synthesis is more favoured than ethanol	[45,46]
Hanseniaspora uvarum, *Schizosaccharomyces pombe*, *Lachancea thermotolerans*, *Saccharomyces kudriavzevii*	Non-*Saccharomyces* sequential inoculation or co-inoculation with *S. cerevisiae*	[14,47–51]
Metschnikowia pulcherrima, *Kluyveromyces* spp., *Candida sake*, *Torulaspora delbrueckii*, *Zygosaccharomyces bailii*	Respiratory consumption of sugars	[52–55]
Saccharomyces cerevisiae	Genetic engineering	[56–58]

S. cerevisiae is efficient at converting sugar to alcohol and has a preeminent tolerance to the stressful conditions encountered during alcoholic fermentation. Thus, one of the methods explored consists in breeding different *S. cerevisiae* strains to select less ethanol producer yeast [43,44]. This strategy could also involve different *Saccharomyces* species, where wine industrial strains can be combined with less known alcoholic species. Indeed, hybrid strains have been described with a reduced efficiency concerning alcohol yields and are able to preserve wine's organoleptic properties after fermentation [43]. Additionally, yeasts could be forced to evolve and adapt to conditions where glycerol synthesis is more favoured than ethanol, for example, conditioning the yeast to higher osmotic pressures [45] or using SO_2 at alkaline pH [46].

Another microbial strategy that has seen growing interest in the last decade involves the use of non-*Saccharomyces* yeasts. These species exhibit physiological properties that are especially relevant during the winemaking process, such as their good fermentative capabilities at low temperatures, resulting in wines with lower alcohol and higher glycerol amounts [10,11]. Several studies have described a reduced ethanol yield (0.2–0.6 % v/v) when using non-*Saccharomyces* and *S. cerevisiae* strains in co-inoculated or sequential cultures [14,47–51,59]. Another alternative to lower the ethanol concentration in wine is to exploit the oxidative metabolism detected in some non-*Saccharomyces* species [52–55]. The supply of oxygen to the fermenters under a controlled flow rate promotes the respiratory consumption of sugars by these non-*Saccharomyces* yeasts.

An additional approach consists in generating low-ethanol yeast strains using metabolic engineering. The principle behind this strategy is the engineering of yeast strains through altered gene expression to modify carbon fluxes in the cell [60]. One of the key target carbon sinks in these approaches has been glycerol, as several research groups have attempted to redirect carbon towards glycerol in order to decrease the flow of carbon to ethanol [56]. Rossouw et al. [43] demonstrated that an alternative metabolite in central carbon metabolism, trehalose, can be targeted as a carbon sink without resulting in the accumulation of undesirable redox-linked metabolites. Besides, the expression in wine yeast of the lactate dehydrogenase gene (*LDH*) from *Lactobacillus casei* has also resulted in reduced ethanol concentration (0.25% v/v less) by diverting carbon to lactic acid production [58].

3.3. Microbial-Based Solutions to Improve Organic Acids Content and to Reduce pH

Among the effects of climate change, the harsh lessening in the acidity of wines has a complex impact on wine quality. Indeed, the low total acidity led to wines with defects in the sensory quality (e.g., less sour/acid taste, changes in the colour) and prone to the implantation of microbial spoilages (reduced wine stability) [24]. These phenomena are likely to be regional-dependent, as recently indicated by Lucio et al. [61], who found an increase of 0.5 units in the pH, also achieving pH values of 3.8–4.0 in the case of wine produced in La Rioja (Spain). Some organic acids are principally associated with fruit composition (tartaric, malic, and citric), while others (succinic, lactic, and acetic acids) are mainly related to the fermentation processes, both to the alcoholic and malolactic [62]. In Table 4, an overview of species/strains selected for their potential of biological acidification of must and wine is given.

Table 4. A list of studies that propose microbial-based solutions that can have potential applications in mitigating the reduced content in organic acids and an increased pH.

Microorganisms Involved	Microbial-Based Mitigating Strategies	References
Candida stellata	Consistent increase in succinic acid content	[63]
Lachancea thermotolerans and *Saccharomyces cerevisiae*	pH reduction and increased total acidity perceived	[59]
Schizosaccharomyces pombe and *Lachancea thermotolerans*	A biotechnological alternative to the traditional malolactic fermentation in red wine production	[64]
Lactobacillus plantarum	Biological acidification using the lactic acid bacterium in pre-alcoholic fermentation	[65]
Candida zemplinina	Moderate production of acetate, succinate, malate, and lactate, with specific nitrogen dependence of acid production	[66]
Lactobacillus plantarum	Selection of MLF starter cultures for high pH must	[67]
Lactobacillus plantarum	Selection of strains to provoke biological acidification in low acidity matrices	[61]
Lactobacillus plantarum	The managing wine acidity depended on the couple LAB/yeast strains co-inoculated	[68]

Non-*Saccharomyces* yeasts and malolactic bacteria are the main reservoirs of microorganisms capable of inducing biological acidification in oenology, due to their physiological features and genetic determinants associated with the production of organic acids [61,69].

The most promising species among non-*Saccharomyces* is *Lachancea thermotolerans* [9,70] due to a considerable aptitude to produce lactic acid [59,64]. Moreover, the use of *L. thermotolerans* has been proposed in combination with *Schizosaccharomyces pombe* [71,72], a yeast capable of converting malic acid in ethanol to mimic classic malolactic fermentation (the decarboxylation of malic acid to lactic acid) [64]. Also, the yeasts *Candida stellata* [73] and *Candida zemplinina* (synonym *Starmerella bacillaris*) [74] have been explored for their possible application in biological acidification in oenological matrices [63,66]. Among malolactic bacteria, *Lactobacillus plantarum*, in reason of the protechnological significance and versatility, extensive applications for their potential to increase the content of lactic acid in the tested matrices have been found [61,65,67,68].

3.4. Microbial-Based Solutions to Modulate/Enhance Sensory Characteristics (Colour, Taste, and Aroma)

The sensory issue represents a more complex matter to provide clear cause–effect solutions. In fact, it is difficult to highlight unambiguous trends associated with climate change (and, consequently, challenging to propose unambiguous microbial-based solutions). However, a plethora of biotechnological solutions that rely on microbial activities are susceptible to applications to cope with the different modifications in sensory attributes addressable to climate change. In Table 5, we provide only a few examples of the microbial-based solutions that are able to modulate/enhance sensory characteristics.

Table 5. A list of studies that propose microbial-based solutions that have potential applications in mitigating modifications of sensory characteristics.

Microorganisms Involved	Microbial-Based Mitigating Strategies	References
Saccharomyces cerevisiae, *Saccharomyces uvarum* and *Saccharomyces montuliensis*	Formation of vinylphenolic pyranoanthocyanins, pigments affecting the colour of the finished wine	[75]
Saccharomyces cerevisiae	Wine yeast are capable to influence volatile sulphur compounds	[76]
Lactobacillus plantarum	Detain enzymes are also involved in improving colour in red wines	[77]
Torulaspora delbrueckii	The yeast in mixed fermentation allows a potential increase of fruity aromas in the wine	[78]
Schizosaccharomyces pombe	The yeast allows increasing the contents of vitisins, especially A type	[78]
Candida zemplinina	The yeast improves vitisin A contents	[79]
Torulaspora delbrueckii and *Saccharomyces cerevisiae*	*T. delbrueckii* in association with *S. cerevisiae* affects the esters content with impact on the aromatic traits of wines.	[80]
Oenococcus oeni and *Saccharomyces cerevisiae*	Co-inoculation of yeasts and lactic acid bacteria as a strategy produces enhancement in wine aroma profile during fermentation	[81]
Saccharomyces cerevisiae	A flor velum *Saccharomyces cerevisiae* strain is able to influence colour and the contents of key aroma compound, susceptible to conceive new red wine types in a climate change scenario.	[82]
Oenococcus oeni	The use of different malolactic starter culture led to modulation in the quality and quantity of volatile organic compounds	[83]
Starmerella bacillaris and *Saccharomyces cerevisiae*	Mixed fermentations could be considered as a tool to enhance the aroma profile	[84]
Hanseniaspora uvarum	Co-inoculation of *Hanseniaspora uvarum* and *Saccharomyces cerevisiae* in order to increase the aromatic profile and lessen the presence of the undesired characters	[85]
Oenococcus oeni	Influence of protechnological and autochthonous strains on compounds relevant for wine aroma, particularly on branched hydroxylated compounds	[86]

3.5. Microbial-Based Solutions to Less Toxic Compounds (Mycotoxins, Biogenic Amines)

During the winemaking process, several microorganisms may cause the depreciation of wine since they can produce undesirable compounds that are toxic to humans, such as biogenic amines (BA) or mycotoxins [7,8,87].

The main microorganisms responsible for BA production in wine are LAB [88] and some non-*Saccharomyces* yeasts [89]. Moreover, several strains of *Enterococcus* spp. and *Staphylococcus* spp. have recently been isolated from must and wine and described as histamine producers [90,91]. Microbial-based solutions that minimize the presence of these toxic compounds in wine are summarized in Table 6.

Table 6. A list of studies that propose microbial-based solutions that can have potential applications in mitigating an increased content in mycotoxin and biogenic amines.

Microorganisms Involved	Microbial-Based Mitigating Strategies	References
Oenococcus oeni	Non-BA producer's selection to carry out the MLF	[92,93]
Schizosaccharomyces pombe	Inhibition of LAB development (and of the consequent BA generation) by removing malic acid and sugars during AF	[94]
Oenococcus oeni, Lactobacillus hilgardii, Lactobacillus brevis	Co-inoculation of *S. cerevisiae* and LAB to control the BA-producing microorganisms	[95,96]
Lactobacillus plantarum, Pediococcus acidilactici	BA degradation	[97–99]
Saccharomyces cerevisiae	OTA reduction by adsorption	[100,101]
Acinetobacter sp., Saccharomyces cerevisiae	OTA degradation by peptidases	[101,102]

One of the main strategies to avoid the presence of BA in wine is the selection of malolactic starter cultures that are unable to produce these toxic compounds [92,93]. Another microbial strategy to reduce the presence of BA in wine is the use of selected yeast strains to induce malic acid consumption, thus avoiding malolactic fermentation and the risks of BA production associated with this phase [94]. Besides, the co-inoculation of yeast and LAB has been proposed as an interesting microbial-based solution to better control BA-producing microorganisms [95,96].

An alternative to the prevention strategies could be the use of BA-degrading microorganisms. Some wine LAB strains belonging to *Lactobacillus* and *Pediococcus* species were demonstrated to be capable of degrading BA, such as histamine, tyramine, and putrescine [97,98]. These strains showed interesting technological properties, suggesting that the ability to degrade BA could also be a criterion to select a new generation of starter cultures [98]. Enzymes isolated and purified from *L. plantarum* and *P. acidilactici* strains, and identified as multicopper oxidases, were able to degrade histamine, tyramine, and putrescine [99]. Such a finding opens a new perspective on the opportunity of employing purified microbial enzymes to deal with the problem of high BA concentrations in wine [103].

Grapes can be infected by mycotoxigenic fungi, of which *Aspergillus* spp. and *Penicillium* spp. producing ochratoxin A (OTA) is of the highest concern [7,8]. Climate is the most important factor in determining contamination once the fungi are established, with high temperatures being a major factor for OTA contamination [104]. Biological decontamination of mycotoxins using microorganisms is one of the well-known strategies to lessen these toxic compounds (Table 6). A promising approach for wine decontamination could be degradation/reduction of OTA by yeasts. Yeasts are efficient bio-sorbents and are used in winemaking to reduce the concentration of harmful substances from the must, which affect alcoholic fermentation [100,101]. Recently, research from Shukla and co-workers [105] suggests that the OTA may also be adsorbed by cells of bacteria, such as *Bacillus subtilis*. Moreover, many different yeast/bacterial strains have been demonstrated to be able to hydrolyze OTA by the action of a putative peptidase [101,102].

4. Conclusions

Climate change threatens food systems, with huge repercussions on food security and on the safety and quality of final products. In this light, it is crucial to develop a "climate-smart food system" [106] tailored to face the complex set of challenges associated with present and future climate trends, in order to ensure food sustainability [107]. We provided here an outline of potential microbial biotechnologies that may be able to tackle the changes in food quality and safety associated with climate change. With this purpose, we used wine production as a model field, considering the socio-economic relevance of this sector and the significant impact not only on the yield and wine quality, but also on the typicity of the wines [108]. Considering on-going research issues and future perspectives, it is always crucial to remember that the food production systems are interdependent structures. In this light, it is mandatory to assess the impact of the proposed biotechnological solution on the technological regimen, on the chemistry of the matrix, and on the protechnological microbiota. In the case of wine, for example, increasing studies are delving into the impact of different non-*Saccharomyces* species/strains on the microbiological [109–111] and chemical [17,112,113] features of wine. One further aspect that deserves attention is the presence of strain-dependent traits that have often been found to be associated with the protechnological and spoilage microbial phenotypes in oenology [16,114,115].

In some cases, biotechnological solutions have been patented, as we recently reviewed in the case of non-*Saccharomyces* yeasts [116]. Microbial-based approaches represent biological methods that can also find application in the production of organic wines. The potential of microbial activities as mitigating strategies in the wine sector renovates interest in the continuous exploration of microbial diversity-associated specific terroirs, autochthonous grapevines, and typical wines [117–119], and on systems that provide rapid, massive, and low-cost screening of the biotechnological potential associated with this microbial diversity [120–123].

Author Contributions: Investigation, C.B., M.F., P.R., F.B., F.G., G.S., and V.C.; conceptualization, C.B., M.F., P.R., F.B., F.G., G.S., and V.C.; literature search, C.B., M.F., P.R., F.B., F.G., G.S., and V.C.; writing—original draft preparation, C.B., M.F. and V.C.; writing—review and editing, P.R., F.B., F.G., and G.S.

Funding: This research was partially funded by the Apulia Region [project DOMINA APULIAE (POR Puglia FESR - FSE 2014-2020-Azione 1.6.–InnoNetwork)] grant number/project code AGBGUK2. Pasquale Russo is the beneficiary of a grant by MIUR in the framework of 'AIM: Attraction and International Mobility' (PON R&I 2014-2020) (practice code D74I18000190001).

Acknowledgments: We thank the Editor and the two anonymous reviewers whose comments have greatly improved this manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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