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Review

Recovery of Energy and Nutrients from Mycotoxin-Contaminated Food Products through Biological Treatments in a Circular Economy Perspective: A Review

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Abstract: Mycotoxins' contamination of food products is a well-known issue that is gaining interest nowadays due to increasing contaminations that are also related to climate change. In this context, and considering the principles of Circular Economy, finding robust and reliable strategies for the decontamination and valorisation of mycotoxin-contaminated products becomes mandatory. Anaerobic digestion (AD) and composting appear as promising biological treatments to degrade mycotoxins and allow for recovering energy (i.e., biogas production) and materials (i.e., nutrients from digestate and/or compost). The aim of the present paper was to carry out an organic revision of the state of the art of energy and materials recovery from mycotoxin-contaminated food products through biological treatments, highlighting results and research gaps. Both processes considered were not generally affected by the contamination of the feedstocks, proving that these compounds do not affect process stability. Mycotoxins were highly removed due to the concurrence of microbiological and physical agents in AD and composting. From the literature review, emerged the points that still need to be addressed before considering large scale application of these processes, which are (i) to deepen the knowledge of biochemical transformations of mycotoxins during the processes, (ii) to assess the fate of mycotoxins' residues and metabolites in soil once digestate/compost are applied, (iii) to evaluate and optimize the integration of AD and composting in order to increase the environmental and economical sustainability of the processes, and (iv) to update legislation and regulations to allow the agricultural reuse of organic fertilizers obtained from contaminated feedstocks.

Keywords: aflatoxins; anaerobic digestion; biogas; composting; decontamination; waste management

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1. Introduction and Aim of the Review

Mycotoxins contamination of food and feed products poses a serious threat to human and animal health, as well as to the environment and economy. Although the issue of mycotoxins has been well known since the second half of the past century, climate change is favoring mycotoxins' contamination of food and feed, mainly due to the raise of air temperature and humidity in temperate climates. Therefore, scientists' attention to the topic is increasing again. In particular, the introduction of innovative strategies to recover energy and/or materials from contaminated products was investigated in numerous papers in the last 10 years. Contaminated waste recycling uplifts popular concepts such as cleaner production, zero-waste policies, sustainability, and bio-based Circular Economy (CE) [1]. Meeting the principles of CE is becoming mandatory in the actual contest of increased energy price and raw materials' scarcity, and the potential recovery of both energy and materials from mycotoxin-contaminated products appears as an interesting but still infrequently explored topic.

In this context, the aim of the present review was to carry out an organic revision of literature findings dealing with biological treatments (i.e., anaerobic digestion and

composting) for the decontamination and valorisation of mycotoxin-contaminated food products. Following a general introduction on mycotoxins, the review describes the state of the art in legislation and disposal of mycotoxin-contaminated food products. Then, the available literature dealing with the recovery of energy and materials from these wastes through biological processes was reviewed to highlight results, potentialities, and research gaps. These, as the latter, as well as future challenges, are then described in depth in the last part of the review. Since aflatoxins are the most representative mycotoxins, the review is mainly focused on this class of toxins, but data coming from studies dealing with other mycotoxins are reported as well, in order to have a comprehensive overview of the topic.

2. Mycotoxins' Generality: Classification, Biosynthesis, and Hazards

Mycotoxins are secondary metabolites produced by different fungi that affect food safety and human health. Mycotoxins are characterized by low molecular weights, and they are commonly produced by fungal mycelia and accumulated in specialized structures of fungi, including conidia and sclerotia. Mycotoxins have several adverse health effects, just like the fungal strains that produce them. Several mycotoxins show acute toxicity, whereas others become harmful only after prolonged exposure (chronic toxicity). Nowadays, about more than 300 mycotoxins are known. Within them, only a few have been tested for their potential toxicities on human health, i.e., aflatoxins (AFs). AFs are a group of highly toxic and carcinogenic mycotoxins produced mainly by the *Aspergillus* spp. fungal species. Chemically, AFs are difuranocoumarin compounds, and the four major AFs are B1, B2, G1, and G2 (AFB1, AFB2, AFG1, and AFG2). The names are based on their blue (B) or green (G) fluorescence under ultraviolet light and their relative mobility by thin-layer chromatography on silica gel. In addition, aflatoxin M1 is a hydroxylated derivative metabolized from AFB1 by cows and secreted in milk [2].

AFs were discovered in 1960 following a severe intoxication affecting the poultry sector in the United Kingdom, known as "Turkey-X disease". More than 100,000 turkeys died after consuming contaminated Brazilian peanuts. The main contaminating fungi isolated from those peanuts were *Aspergillus flavus* [3]. For a long time, the study of toxic mold metabolites became a "hot topic" in agriculture. In fact, the 15 years between 1960 and 1975 were labelled as a "mycotoxin gold rush" because so many chemical researchers joined the search for mycotoxins, isolating hundreds of fungal metabolites with toxic properties [4,5]. AF-producing fungi are native to warm arid, semi-arid, and tropical regions with climate changes resulting in large fluctuations in the quantity of AF producers [6]. Furthermore, these fungi can tolerate conditions of relative drought and survive with water activity (aw) around 0.70–0.80, the water activity being an estimation of the free water available for biochemical processes (aw < 0.6 does not allow microbial proliferation; aw in the range 0.7–0.8 allows the proliferation of only drought-resistant microbes). These fungi are particularly favored by the hot-humid climate (90–98% relative humidity) and by drought conditions during the vegetative season. The growth of some mycotoxigenic species can be stimulated by slightly higher CO_2 concentrations, interactions with the temperature and the availability of water, hydrous stress, crop genotype, insect damage and agricultural practices. Thus, the percentage of fungi strains able to produce AFs in a fungal population varies in different areas and different years. *Aspergillus* section *Flavi* are plant pathogens and saprophytic during most of their life cycle and they are well adapted to tropical and sub-tropical areas. *Aspergillus* Section *Flavi* are not very aggressive, and they tend to contaminate damaged or stressed crops, although they sometimes invade the seeds directly. *Aspergillus flavus* is the most aggressive species and it dominates on all the commodities and is probably supported by its ability to produce pectinase and cutinase, a relevant aid in host penetration [7].

A. flavus scarcely competes under cool conditions, and its occurrence in cool weather areas is lower if compared to warmer regions, where AFs' producers are commonly present in the soil, air, and crop surface [8]. Thus, composition and origin areas make some food products more susceptible to AFs' contamination with respect to others. (e.g., flour for

human use and animal oils, oilseeds excluding fine oils, peanuts, cocoa products, coffee, wine and beer, milk, and spice-containing products). Moreover, AFs' contamination may occur also during the storage and transformation of food products.

AF biosynthesis is a complex pathway, where at least 23 enzymatic reactions are involved in their formation. The AFs' biosynthesis genes of *A. flavus* and *A. parasiticus* are highly homologous, and the order of these genes has been demonstrated to be the same within the cluster. These genes include key regulatory genes (aflR and aflS), and a series of up and downstream structural genes [9]. AFB1 biosynthesis is affected by several environmental factors, such as stress, quorum sensing, and the protein signaling pathway, as well as by subcultures and changes in the morphology of producing cells. Moreover, the biosynthesis is higher in acidic mediums, whereas it is inhibited in alkaline conditions [10]. Changes in environmental temperature, the interactions between water activity, and temperature influence the expression levels of regulatory genes (aflR and aflS) and AFs' production [11].

AFB1 has been classified as a known human carcinogen of the Group 1 by the International Agency for Research on Cancer (IARC). AFB1 induces chromosomal aberrations, micronuclei, sister chromatid exchange, unscheduled DNA synthesis, and chromosomal strand breaks, and forms adducts in human cells [12]. The severity of DNA toxic effects in humans or animals varies with exposure levels, exposure time, and nutritional status. For large doses of exposure, this agent can induce acute damage of DNA, such as inhibiting DNA synthesis, subsequently resulting in the lethal changes of liver cells, hepatocellular severe degeneration, and necrosis. Long times of low-level exposure to AFs mainly induce chronic DNA damage, resulting in neoplasia in many animals or humans. Chronic DNA damages induced by AFB1 include AFB1-DNA adducts, oxidative DNA damage, DNA strand break damage, and gene mutation [13].

AFB1 is metabolized by cytochrome P450 enzymes to its reactive form, AFB1-8,9-epoxide (AFB1-epoxide), which covalently binds to DNA. The formation of the 8,9-dihydro-8-(N7-guanyl)-9-hydroxy–AFB1 (AFB1-N7-Gua) adduct proceeds by a precovalent intercalation complex between double-stranded DNA and the highly electrophilic, unstable AFB1-epoxide isomer. After that, the induction of a positive charge on the imidazole ring of the formed AFB1-N7-Gua adduct gives rise to another important DNA adduct, a ring-opened formamidopyridine AFB1 (AFB1-FAPy) adduct. The accumulation of AFB1-FAPy adduct is characterized by time-dependence and may be of a biological basis of genes' mutation because of its apparent persistence in DNA [13].

3. Mycotoxin Contamination of Food Products: Issues, Legislation, and Actual Disposal

Cereals represent the main source for human and animal nutrition. FAO's latest forecast for world cereals production in 2020 has been lifted by 17 million tons from the previous report in 2019 to 2761 million tons, now pointing to a 1.9% increase year-after-year [14]. At the same time, these crops are highly susceptible to AF contamination. Therefore, cereal-derived food products may represent one of the main sources of human exposure to AFs. For instance, it was estimated that over 5 billion people worldwide are at risk of chronic exposure to AFs in corn-derived food [15]. Since cereals are fundamental in human and animal nutrition, any damage to their production causes significant economic losses and health issues. In fact, AFs' contamination in food products primarily inflicts economic rather than health burdens in industrial countries, reducing the economic value of crops and causing the disposal of large amounts of food products. For instance, losses to the US corn industry from AFs' contamination could exceed $1 billion during years with warm summers and drought, which are conditions that favor fungi proliferation [16]. Conversely, in low-income countries, the health impacts of AFs are more severe. Many individuals are malnourished and chronically exposed to high AF levels, resulting in deaths from aflatoxicosis and liver cancer [17].

As well as cereals, soybean and other raw materials can be contaminated with mycotoxin-producers fungi, either during vegetation in the field or during storage, and

likewise during the processing. For instance, Binder et al. [18] reported that in 122 samples of soybean meals analyzed in Oceania and Asia, about 10% was contaminated by mycotoxins (i.e., deoxynivalenol, zearalenone, fumonisins, aflatoxins). Soybean is often attacked by fungi during cultivation, which significantly decreases its productivity and quality in most production areas. The largest producers of soybeans in the world are the United States of America, Brazil, Argentina, China, and India. The climatic conditions in soybean-growing regions (moderate mean temperature and relative humidity between 50% and 80%) provide optimal conditions for fungal growth [19]. The soybean matrix has been rarely studied compared to cereals in relation to fungal and mycotoxin contamination. Consequently, most of the information reported in the present paper are related to cereal food products (i.e., recycling through biological processes).

A key tool to ensure the flow of information and enabling swift reaction when risks to public health are detected in the food chain is the Rapid Alert System for Food and Feed (RASFF). The increasing issue of mycotoxins' contamination of food products was confirmed, analyzing the number of RASFF notifications for two decades (2001–2010; 2011–2020). The number of notifications of serious mycotoxins' contaminations of cereals and bakery products increased from 229 (2000–2009) to 273 (2011–2020). Within these notifications, AFs' contaminations represented about 50% (2001–2010) and 45% (2011–2020). Moreover, other food products highlighted an increase in RASFF notification between the two decades considered, i.e., milk and milk products (from 2 to 14 notifications).

Global climate change may cause considerable economic losses and health alerts in Europe and in the world due to its impact on AFs' occurrence in crop cultivation and storage. The problem of mycotoxins in food products is becoming worse due to the correlation between contamination and climate change. Battilani [20] used a mechanistic model to assess the AFB1 corn contamination increase caused by the actual climate change trend in the next 100 years. This model predicts the A. flavus growth and AFB1 production in corn, using weather data as the input linked to a crop phenology prediction module (based on temperature sums, with a focus on the crucial stages of flowering and ripening, or date of harvest). Mean AFI (aflatoxin hazard indexes) increased by 92% and 149% when moving from the present scenario to the +2 °C and +5 °C scenarios, and the areas with the major AFs' contamination increase were Eastern Europe, Balkan Peninsula, and the Mediterranean region.

The knowledge that mycotoxins can have serious effects on humans and animals has led many countries to regulate their occurrence in food and feed in the last decades. The appropriate balance between addressing food safety concerns and limiting disruption to trade is an intricate and contentious issue because it involves many factors and interested parties. The settings of limits and regulations depends upon several factors, i.e., (1) the availability of toxicological data, (2) the availability of data on the occurrence of mycotoxin in various commodities, (3) knowledge of the distribution of the mycotoxin concentrations within a lot, (4) availability of analytical methods, (5) legislation in countries with which trade contacts exist, and (6) need for sufficient food supply [21]. The legislation prescribes mandatory or guideline limits, often taking the form of product standards. However, diverging perceptions of tolerable health risks have led to widely varying standards among different national or multilateral agencies. The risks associated with mycotoxins depend on both hazard and exposure. Whilst the hazard of mycotoxins to individuals is probably more or less the same all over the world, the exposure is not the same, because of different levels of contamination and dietary habits in various parts of the world [22]. This last fact explains the difference in the regulatory limits between countries. These standards offer public health protection in industrialized countries, but they arguably have little effect in less developed countries, for several reasons: (1) the food consumed from subsistence farms are not controlled; (2) many people in less development countries consume high levels of corn and groundnut products; therefore, AFs' exposure is higher; (3) the less developed countries that attempt to export products abroad may find their export markets severely jeopardized by strict AF standards [23].

Mycotoxin regulations have been established in more than 100 countries [24]. The EU has one of the highest food safety standards in the world, largely thanks to the solid set of EU legislation in place, which ensures that food is safe for consumers. Table 1 reports a comparison between the EU and the US regulations concerning food and feed contaminations by AFs. The EU harmonized regulations for the maximum levels of mycotoxins in food and feed among its member nations in the early 2000s [25,26]. Moreover, European Commission [27] laid down the methods of sampling and analysis for the official control of the levels of mycotoxins in foodstuffs, whereas the European Commission [28] indicated the need for monitoring the presence of ergot alkaloids in food and feed. In the case of lots intended for industrial purposes, neither maximum limits nor guidance levels have been established.

Table 1. Maximum levels for aflatoxin contaminants in food- and feedstuffs in European Union and United States of America.

Product	Final Consumer	EU [a] (μg kg^{-1})	USA [b] (μg kg^{-1})
Corn	Humans	4	20
Corn (to be sorted)	Humans	10	-
Groundnuts	Humans	4	20
Groundnuts (to be sorted)	Humans	15	-
Corn	Immature animals	10	20
Corn	Mature animals	20	100
Corn	Mature feedlot cattle	20	300
Corn	Dairy cattle	5	20
Milk	Humans	0.05	0.5
Milk	Infants	0.025	0.5

[a] [25,26] [b] [29].

Regarding the products exceeding the maximum limit, Commission Regulation EC 1881/2006 [25] states that to *ensure an efficient protection of public health, products containing contaminants exceeding the maximum levels should not be placed on the market either as such, after mixture with other foodstuffs, or used as an ingredient in other foods*. So far, European legislation does not indicate how food products contaminated by AFs should be disposed and no European Waste Catalogue Code was attributed to these wastes. For this reason, the classification of AF-contaminated corn as dangerous or non-dangerous waste is still pending. Similarly, in the USA there seems to be no specific protocol prescribed for the disposal of AF-contaminated commodities at the federal level. Chapter 7 of the U.S. Code of Federal Regulations only reports guidelines on the *disposal of meal contaminated by aflatoxin* [30]. However, the instructions state only that *the meal be disposed of for non-feed purposes only* but does not elaborate how the disposal should be carried out.

In the last decades, the physical, chemical, and biological systems for AFs' decontamination of food products have been investigated, demonstrating that the biological ones are more advantageous with respect to the others for several reasons (i.e., integrity of the treated product, requirement of simple infrastructure, simple and safe procedures) [31,32]. Nowadays, food products contaminated or recovered after AFs' decontamination cannot be placed on the market and this represent a major obstacle to the spread of AFs' decontamination treatments. The disposal of AF-contaminated food products is mainly carried out through landfilling, burying, and incineration. The main advantages and disadvantages of systems used for AFs-contaminated food products are summarized in Table 2.

Burying has spread in developing countries to dispose of AF-contaminated food products. Soil contains numerous microorganisms, some of which have been demonstrated to degrade AFs. *Flavobacterium auranticum* [33], *Mycobacterium fluoranthenivorans* [34], *Psuedomona saeriginosa* [35], as well as *Aspergillus niger* [36] degrade AFs. Furthermore, AFs have been demonstrated to bind tightly to some clays, such as those rich in sodium calcium aluminosilicates [37] and such binding can sequester the AFs, making them less harmful to susceptible soil biota. The disposal of AF-contaminated materials by burying

may also have its disadvantages. There is evidence that some plants may take up AFs from the soil [38,39].

Table 2. Main advantages and disadvantages of different disposal systems for aflatoxin-contaminated food products. AFs: aflatoxins.

Disposal System	Advantages	Disadvantages
Landfilling	Low disposal costs	Potential soil and water contaminations; slow AFs' removal
Burying	Low disposal costs	Potential soil and water contaminations; slow AFs' removal; plant uptake of AFs
Incineration	Low disposal costs (for low-technology incineration systems); complete AFs' removal	Potential air contamination (for low-technology incineration systems); requirements of energy, investments and specialized staff (for high-technology incineration systems)
Anaerobic digestion	Recovery of energy and nutrients (biomethane and digestate); moderate efficiency for AFs removal	Requirements of initial investments and specialized staff
Composting	Recovery of nutrients (compost); high efficiency for AFs' removal	Requirements of energy

Incineration, if carried out to completion, is probably the most effective disposal process, as it destroys the AF molecule. In fact, AFs decompose at 269 °C [40] and incineration temperatures usually reach upwards of 500 °C. In addition, incineration ashes, largely minerals, could be used as a supplement to agricultural fertilizer. In developing countries, emissions from incineration plants are often not controlled and permeate the surrounding environment and are conveyed and dispersed by prevailing winds. Moreover, the products of the incineration of plant materials are reported to include highly toxic polyaromatic hydrocarbons that can be detrimental to the biota near the operation [41].

In the last few years, the recycling of AF-contaminated food products through biological treatments have been investigated. The production of bioethanol from AF-contaminated corn has been studied only recently, highlighting the need for further studies [42]. The first results demonstrated a scarce removal of AFs during bioethanol fermentation, and, in addition, bioethanol quality was negatively affected by AFs. Conversely, there is an increasing interest for the anaerobic digestion and composting of AF-contaminated food products, mainly due to the possible recovery of energy (biomethane) and plant nutrients (digestate and compost). At the same time, both anaerobic digestion and composting have been proved to degrade with high efficiency AFs. The number of papers dealing with energy and nutrients' recovery from mycotoxin (and more specifically, AFs)-contaminated food products is increasing steadily, and, in this context, the aim of the present review is to define the state-of-the-art research and to highlight the research gaps in this topic.

4. Biological Treatments for Energy and Nutrients' Recovery from Contaminated Food Products

4.1. Biological Treatments for Energy and Nutrients' Recovery from Organic Wastes

Anaerobic digestion (AD) and composting are the most widespread biological systems used for organic waste treatments. These technologies allow for recovering energy and nutrients from livestock residues, sludge, the agro-industrial, municipal and food wastes, making their disposal more sustainable in both economic and environmental perspectives.

AD and composting are two distinct biological processes, where organic matter is biodegraded under anaerobic and aerobic conditions, respectively. AD can degrade organic wastes to biogas and digestate through four subsequent phases, (1) hydrolysis, (2) acidogenesis, (3) acetogenesis, and (4) methanogenesis [43]. Biogas is a gas mixture mainly composed by methane and carbon dioxide (55–70% and 30–45%), as well as small amounts of other gases (oxygen, sulphuric acid, and hydrogen) [44]. Biogas can be used as an alternative

energy source through its combustion in boilers or combined heat and power units; however, the interest in biogas conversion to high-value products is increasing recently [44,45]. Digestate is widely considered as a potential organic fertilizer, being rich in plant macronutrients (N, P and K) and organic matter [46–48]. Ammonium-N is the most abundant form of N in digestate, making digestate a readily available N fertilizer for plants [46,48]. Concerns emerged regarding organic matter stabilization in digestate [49–51], but Tambone et al. [52] stated that the well-performed AD can produce stabilized digestate due to the mineralization of labile organic compounds and persistence of recalcitrant organic molecules. Nevertheless, digestate often requires post-treatments to improve its agricultural reuse (i.e., to reduce water content). AD can be operated at psychrophilic (18–20 °C), mesophilic (35–40 °C) and thermophilic (50–60 °C) temperature regimes [53], the last two conditions being more effective for organic matter degradation and biogas production. Besides some disadvantages (e.g., slow degradation, need for post-treatment of digestate, process instability), AD is characterized by several important advantages such as net energy production, reduced odor, and small area requirement [43,54].

Composting degrades aerobically organic wastes to compost and two main by-products (heat and carbon dioxide) [55]. Composting is a self-heating process that proceeds through three main phases, (1) mesophilic (25–40 °C), (2) thermophilic (55–65 °C) and (3) cooling and maturation. Compost is defined as a nutrient-rich organic amendment able to provide N, P, K, and organic matter to soil [56]. Differently from digestate, organic-N is predominant in compost, making it a long-term N source for plants [57]. During composting, labile organic matter is mineralized, and complex recalcitrant materials tend to concentrate, conferring stability to the compost [57,58]. Compost also positively affects physical properties of soil (e.g., porosity and water-holding capacity) mainly due to its reduced bulk density [59]. Lin et al. [43] reviewed the composting of organic wastes and indicated the fast degradation, small investments, and compost reuse as the main advantages of this process, the gas emissions, large area requirements and the net energy consumption being its main disadvantages.

Although AD and composting can effectively reduce environmental and financial costs of organic waste disposal, the possible contamination of soil, water and air related to the agricultural reuse of digestate, and compost emerged recently as a critical issue. In fact, the environment contamination derived by soil fertilization with waste-derived fertilizers can rise risks to human, animal, and plant health [60]. A large set of emerging contaminants can occur in organic wastes (e.g., antimicrobials, antimicrobial resistance genes, pesticides, heavy metals) and their fate during AD, and composting was recently reviewed by Congilosi and Aga [61]. Sertillanges et al. [62] evaluated the fate of organic micro-pollutants during the industrial scale treatment of organic wastes and observed that process type and compound characteristics mainly influence the pollutants' fate, the waste origin not being significant. For instance, the antimicrobials demonstrated a variable fate during AD and composting. Some studies stated that various antimicrobials degraded completely, whereas others reported only a partial degradation [61,63–65]. Similar results have been reported for other emerging pollutants such as antimicrobial resistance genes, hormones, and pesticides [66–68]. It seems that the synergic effects of microbial activity, temperature, pH, binding to organic matrix, and mineralization during AD and composting contribute to organic pollutants' degradation [61]. Concerning the threat of heavy metals, AD and composting cannot degrade them but biological treatments are known to reduce their bioavailability [69].

4.2. AD of Contaminated Food Products

AD of AF-contaminated matrices for energy and nutrients' recovery has been investigated only in the last decade. To have a complete view of the topic of mycotoxins' effects on AD, the present review includes also papers dealing with mycotoxins different from AFs.

Recent papers investigated the effect of mycotoxins on biogas production and digestate quality using both batch and CSTR (continuous-stirred tank reactor) trials, as well as mycotoxins' fate during the anaerobic process (Tables 3 and 4).

Table 3. Biogas production and process stability.

Mycotoxin	Anaerobic Digestion	Organic Substrate	Biogas Production (NL/kg TS)	Methane (% *v*/*v*)	Process Stability	References
AFB1	Batch mesophilic	Corn grain	579–617	57–60	n.a.	[70]
	CSTR mesophilic	Corn grain	580	58	VFA, VFA/alkalinity, ammonium-N in optimal range	
AFB1	CSTR mesophilic	Corn flour	600–625	50–55	VFA, VFA/alkalinity, pH in optimal range	[71]
FB1 + FB2 + FB3	Batch mesophilic	Corn silage	170–180	55	pH in optimal range	[72]
	Batch mesophilic	Wholewheat flour	340	55	n.a.	
	Batch mesophilic	Wheat bran	330	55	n.a.	
DON + T-2 + HT-2	Batch mesophilic	Wheat fine bran	350	55	n.a.	[73]
	Batch mesophilic	Wheat semolina	350	50	n.a.	
	Batch mesophilic	Wheat fine middlings	300	50	n.a.	
AFB1 + DON + ZEN + OTA + FB1 + T-2 + ergot alkaloid mix	Batch mesophilic	Corn grain	500–550	55–60	n.a.	[74]
	Batch thermophilic	Corn grain	580–620	55–60	n.a.	
DON + 3-ADON + 15-ADON + AOH + T-2 + ZEN + FB1 + FB2 + ENNB	CSTR mesophilic	Corn grain	680	60–65	VFA, VFA/alkalinity, pH in optimal range	
DON	Batch mesophilic	Wheat flour	667.2–742.8	50–55	n.a.	[75]
	CSTR thermophilic	Corn grain	690	60–65	VFA, VFA/alkalinity, pH in optimal range	[76]
AFB1	CSTR mesophilic	Corn grain	700–800 (25 μg kg^{-1} AFB1)	60–65	VFA, VFA/alkalinity, ammonium-N, and pH in optimal range	
	CSTR mesophilic	Corn grain	0 (100 μg kg^{-1} AFB1)	0	VFA accumulation and pH decrease to inhibiting values	
AFB1 + DON + ZEN + OTA + FB1 + T-2 + ergot alkaloid mix	Batch mesophilic	Corn grain	500–550	55–60	n.a.	
	Batch thermophilic	Corn grain	580–620	55–60	n.a.	
DON + 3-ADON + 15-ADON + AOH + T-2 + ZEN + FB1 + FB2 + ENNB	CSTR mesophilic	Corn grain	680	60–65	VFA, VFA/alkalinity, pH in optimal range	
	CSTR thermophilic	Corn grain	690	60–65	VFA, VFA/alkalinity, pH in optimal range	

n.a.: not available.

Table 4. Mycotoxins fate during AD.

Mycotoxin	Initial Contamination (μg kg^{-1})	Anaerobic Digestion	Organic Substrate	Average Mycotoxin Removal	References
AFB1	0.54–110.0 7.2	Batch mesophilic CSTR mesophilic	Corn grain Corn grain	69–87% 61%	[70]
AFB1	2–470	CSTR mesophilic	Corn flour	12–95%	[71]
FB1 + FB2 + FB3 + AFB1	241.5–13874 (FB1) + 866.5–3877 (FB2) + 42.5–3591 (FB3) + 251 (AFB1)	Batch mesophilic	Corn silage	20–60% (FB1, FB2, FB3) 55% (AFB1)	[72]
DON + T-2 + HT-2	368–12,916 (DON) + 5–65 (T-2+HT-2)	Batch mesophilic	Wholewheat flour	89.9% (DON) 100% (T-2, HT-2)	[73]
	368–12,916 (DON) + 5–65 (T-2 + HT-2)	Batch mesophilic	Wheat bran	88.5% (DON) 100% (T-2, HT-2)	
	368–12,916 (DON) + 5–65 (T-2 + HT-2)	Batch mesophilic	Wheat fine bran	83.9% (DON) 100% (T-2, HT-2)	
	368–12,916 (DON) + 5–65 (T-2 + HT-2)	Batch mesophilic	Wheat semolina	82.1% (DON) 100% (T-2, HT-2)	
	368–12,916 (DON) + 5–65 (T-2 + HT-2)	Batch mesophilic	Wheat fine middlings	98.7% (DON) 100% (T-2, HT-2)	
AFB1 + DON + ZEN + OTA + FB1 + T-2 + ergot alkaloid mix	40 (AFB1) + 300 (DON) + 100 (ZEN) + 50 (OTA) + 100 (FB1) + 100 (T-2) + 40 (ergot alkaloid mix)	Batch mesophilic	Corn grain	>90% (AFB1, DON, ZEN, OTA, T-2) 70% (FB1) 64% (ergot alkaloid mix)	[74]
		Batch thermophilic	Corn grain	>90% (AFB1, DON, ZEN, OTA, T-2) 85% (FB1) 98% (ergot alkaloid mix)	
DON + 3-ADON + 15-ADON + AOH + T-2 + ZEN + FB1 + FB2 + ENNB	4413 (DON) + 729 (3-ADON + 15-ADON) + 14 (AOH) + 28 (T-2) + 1052 (ZEN) + >80 (FB1 + FB2) + >80 (ENNB)	CSTR mesophilic	Corn grain	>99%	
		CSTR thermophilic	Corn grain	>99%	
DON	1976–80,000	Batch mesophilic	Wheat flour	100%	[75]
AFB1	25 100	CSTR mesophilic CSTR mesophilic	Corn grain Corn grain	18.8% * 37.2% *	[76]

*: accumulation of AFB1.

4.2.1. Biogas Production and Digestate Quality

The first report on the AD of mycotoxin-contaminated corn was published by Salati et al. [70] (Table 3). They carried out both batch and continuous-stirred tank reactor (CSTR) experiments fed with pig slurry and AFB1-contaminated corn. In batch tests, a stable methane production (57–60% v/v) was achieved in all the trials, even when the highest concentration of AFB1 was tested (110 μg kg corn^{-1} wet weight). The cumulative biogas production was in accordance with values reported in literature for corn grain (350–375 NL kgTS^{-1}). CSTR experiments were operated with 40 days of HRT through the daily addition of the fresh contaminated feedstock to reproduce a full-scale digestion process. Biogas production and chemical parameters (e.g., volatile fatty acids, ammonia content) of the CSTR experiments did not demonstrate differences between non-contaminated and contaminated tests. Salati et al. [69] concluded that AFB1 did not affect the AD of pig slurry and corn grain. These results were in accordance with Giorni et al. [71], who demonstrated that mycotoxins do not affect biogas production from the AD of cattle manure, corn silage and corn flour. They studied two different levels of AFB1 and fumosin contamination (70 and 470 μg kg flour^{-1} AFB1 and 1200 and 3700 μg kg flour^{-1} fumosins) using CSTR reactors operating with an HRT of 50 days. Biogas quantity and quality were not affected by mycotoxins, as well as process stability (FOS/TAC ratio was in the optimal range throughout the experiments).

Other studies support the conclusion that biogas can be effectively recovered from mycotoxin-contaminated matrices [72–75]. When batch AD tests carried out using corn as feedstock were spiked with 40 μg kg^{-1} AFB1, 300 μg kg^{-1} DON, 100 μg kg^{-1} ZEN, 50 μg kg^{-1} OTA, 100 μg kg^{-1} FB1, 100 μg kg^{-1} T-2 and 40 μg kg^{-1} of ergot alkaloid mix, neither biogas production nor its quality were affected [74]. In the same study, the semi-continuous AD of contaminated corn (4413 μg kg^{-1} DON, 729 μg kg^{-1} 3-ADON + 15-ADON, 14 μg kg^{-1} AOH, 28 μg kg^{-1} T-2, 1052 μg kg^{-1} ZEN, 170 μg kg^{-1} FB1 + FB2 and >80 μg kg^{-1} ENNB) using 25 days of HRT demonstrated a stable and productive process, even in the face of a continuous feeding of heavily contaminated material [74]. Ferrara et al. [72] observed that fumosins' contamination of silage (241.5–13,874 μg kg^{-1} FB1, 86.5–3877 μg kg^{-1} FB2, 42.5–3591 μg kg^{-1} FB3) did not hamper the methane production in batch tests.

These results were in contrast with the findings described by Tacconi et al. [76], who studied the effect of AFB1 on a semi-continuous anaerobic digestion process feed with pig slurry and corn grain. They tested the effects of the increasing AFB1 concentration on AD, operating with 15 days of HRT and high mycotoxin concentrations (25, 50, and 100 μg kg mixture^{-1} wet weight). The daily addition of AFB1 concentration higher than 25 μg kg^{-1} caused the inhibition of methanogenic bacteria, leading to volatile fatty acids' accumulation, pH decrease and AD failure. Probably, the short HRT and the high organic loading rate used in the experiments could have affected the AD, making the process more susceptible to inhibition mechanisms.

Although most of the literature concerning the AD of mycotoxin-contaminated matrices is regarding corn and silage, contaminated wheat products were also studied in AD [73,75]. Seven naturally contaminated flour samples (DON = 0, 1976, 4586 and 10,470 μg kg^{-1}) or artificially spiked commercial flour (DON = 0, 8000 and 80,000 μg kg^{-1}), were digested in batch tests. The biogas potential of the wheat flours ranged from 667.2 to 742.8 Nm^3 ton^{-1}, demonstrating no significant effect of the DON concentration on the biogas volume and quality produced [75]. More recently, Soldano et al. [73] investigated the AD of different milling products of durum wheat (whole wheat flour, bran fractions, semolina, and fine middling) contaminated with DON and T-2 + HT-2 toxins. No significant correlations were found between the potential biomethane production and mycotoxins' initial concentrations, independently from the milling fraction.

All the reviewed literature indicates the potential for energy recovery from contaminated feedstock through AD. In fact, it appears clear that biogas production and process stability are not affected by even heavy contaminated feedstock. The possible long-term inhibi-

tion of AD could be easily avoided by interchanging contaminated and non-contaminated feedstock. This strategy could be feasible, considering that mycotoxins' contamination is a seasonal issue.

Concerning nutrients' recovery through agricultural reuse of the digestates obtained from AD of the mycotoxin-contaminated feedstock, further assessments are needed. Besides a high fertilizer potential related to the high content of ammonium-N, P and K, the agricultural reuse of digestate faces agronomic and environmental issues (e.g., residual phytotoxicity, high salinity, mycotoxin residues) [76].

4.2.2. Mycotoxins' Fate during AD

Fate of mycotoxins throughout the AD process is a major concern for the feasible recovery of energy and nutrients from contaminated products. Indeed, digestate utilization depends on the complete removal of mycotoxins, to obtain a safe product that is spreadable on agricultural soil.

Many authors have studied the microbial degradation of mycotoxins [33,77] and different bacteria commonly found in AD microflora demonstrated the ability to degrade mycotoxins (i.e., *Pseudomonas* spp. and *Bacillus* spp.) [35,78]. In addition, AFB1 has been reported to bind to the bacterial surface of several *Lactobacillus* strains by hydrophobic interactions [79].

The literature agrees that AD can effectively remove mycotoxins from corn- and wheat-contaminated products [70–75] (Table 4). Mycotoxin removal depended mostly on the type of mycotoxin and the operational conditions of AD, whereas the matrix seems to be irrelevant of the removal processes. Overall, the synergic effect of microbial activity, temperature, pH, binding to cell walls, and mineralization is considered responsible for mycotoxin removal during AD.

Some classes of mycotoxins were removed easier during AD with respect to the others. For instance, DON, T-2, and HT-2 demonstrated an average removal higher than 90% in the batch and CSTR mesophilic AD of corn and wheat products [73–75]. Other mycotoxins demonstrated a lower removal in anaerobic conditions (i.e., the ergot alkaloid mix, and fumosins' concentrations decreased by about 60% and 20–60% in the batch of mesophilic AD, respectively) [72,74]. AFB1 was removed with a moderate efficiency during AD, demonstrating a removal range of about 55–90% [70,72,75]. Tacconi et al. [76] is the only study that reports the AFB1 accumulation during CSTR AD, and it was probably related to the daily addition of heavy contaminated feedstock to the digester combined with a short HRT and a high OLR.

The temperature regime seems to affect mycotoxin removal, whereas batch and CSTR processes did not differ in contaminants' degradation efficiency. De Gelder et al. [74] observed significant differences in mycotoxins' removal between the mesophilic and thermophilic batch of AD, with the thermophilic process being more efficient than the mesophilic one. Higher thermophilic degradation has previously been described by other authors for the degradation of several emerging organic pollutants (i.e., polycyclic aromatic hydrocarbons, di-2-(ethyl-hexyl)-phtalate, estradiol, endocrine disrupting compounds, and non-steroidal anti-inflammatory drugs) [80,81].

No evidence of the feedstock composition influence on mycotoxin removal was found in literature, and this is in accordance with Sertillanges et al. [62], who did not report the global influence of the substrate type on organic micropollutants' degradation during AD.

Nowadays, the literature does not detail whether mycotoxins' removal during AD wis due to complete mineralization, binding to cells' walls or transformation to other compounds. Tacconi et al. [76] detected the AFB2 during the CSTR digestion of AFB1-contaminated corn grain and they explained it through the acid-catalyzed water addition to the vinylene group of the dihydrofuran moiety of AFB1. This represents a major issue that should be addressed, since mycotoxins should be mineralized or transformed into non-toxic compounds to ensure a safe reuse of digestate in agriculture. The biotransformation of emerging organic contaminants in homologous compounds was also addressed

by Zhang et al. [66], for steroid hormones such as androgens, progestogens, and glucocorticoids They demonstrated the negative removal (accumulation) of hormones during biological treatments of contaminated manure due to the bioconversion from hormones' conjugate forms or to the transformation of one hormone into another.

4.3. Composting of Contaminated Products

Differently from AD, the composting of mycotoxin-contaminated matrices is still almost unexplored. Only a few papers reporting the effects of mycotoxins on composting and compost quality can be found in the literature, highlighting the need for further investigation regarding this treatment. Table 5 presents the main findings about the composting of mycotoxin-contaminated products.

Table 5. Composting of mycotoxin-contaminated products: process characteristics and mycotoxins' fate.

Mycotoxin	Initial Contamination (μg kg^{-1})	Organic Substrate	Composting Process	Peak Temperature (°C)	Average Mycotoxin Removal	References
AFB1	100	Corn grain and pig slurry	Pilot scale, passive aerated, static composting	75.5	85.7%	[82]
		Corn grain and organic fraction of municipal solid wastes		74.8	97.3%	
AFB1 + AFB2 + AFG1 + AFG2	195.4 (AFB1) + 22.2 (AFB2) + 2.9 (AFG1) + 1.2 (AFG2)	Peanut meal	Laboratory scale, actively aerated, continuously mixed composting	36.4	58.6% (AFB1) 54.5% (AFB2) 96.6% (AFG1) 83.3% (AFG2)	[83]
	2955 (total AF)	Peanut seeds, peanut shells, peanut leaves, and cowpea pods	Pilot scale, actively aerated, 3-times a week mixed composting	n.a.	77%	
OTA	0.37–1.66	Coffee pulp and husks + bulking material	Real scale, passive aerated, monthly mixed composting	n.a.	400–600% *	[84]

n.a.: not available. *: accumulation of OTA.

4.3.1. Composting Process Evolution and Compost Quality

The potential of plant nutrients' recovery from mycotoxin-contaminated products through composting was explored only in the last few years [82,83]. These studies evaluated the effect of mycotoxins on the composting evolution, compost quality, and mycotoxins' fate (Table 5). The temperature behavior during composting is an adequate real-time indicator for the optimal conditions for supporting the microbial activity and the organic matter degradation. Moreover, a minimum temperature of 55 °C must be maintained for three days during the thermophilic phase to obtain biomass hygenization [57]. An effective composting process should also produce mature and stable compost, and it can be assessed through C/N ratio determination, phytotoxicity assays, and a water-soluble organic matter analysis [57,85–87]. Finally, the absence or low level of toxic compounds (e.g., heavy metals) should be attained after composting to achieve the safe recycling of plant nutrients.

Akoto et al. [83] reported the first assessment of composting for peanut meal decontamination from aflatoxins. They carried out both laboratory scale and pilot scale experiments using peanut by-products contaminated with AFB1, AFB2, AFG1, and AFG2. Temperature profiles demonstrated a regular behavior, indicating that aflatoxins did not produce toxic effects on thermophilic microflora. Compost obtained from the pilot scale experiment demonstrated acceptable contents of nitrogen, phosphorous, potassium and micronutrients, as well as a high maturation (C/N ratio was about 4.5) and low content of heavy metals.

Results from Akoto et al. [83] were confirmed in a later study where AFB1 contaminated corn grain (100 μg kg^{-1} AFB1, wet weight) was co-composted using two different co-substrates (pig slurry and organic fraction of municipal solid wastes) [82]. AFB1 did not affect the temperature profile during the active phase of composting, and a high temperature were reached (75.5 °C and 74.8 °C for the pig slurry and organic fraction of municipal

solid waste mixtures, respectively). AFB1 did not affect maturation and stabilization processes during the composting, and the final products were characterized by an optimal C/N ratio (about 10), absence of phytotoxicity (germination index was higher than 100%, probably due to high nutrients' concentration and the presence of phytohormone-like substances with biostimulant activity) and reduced content of water-soluble organic matter.

Preliminary studies demonstrated that the composting process evolution and compost quality are not affected by mycotoxins' contamination of the feedstock. Similar results were obtained by other authors, who demonstrated that antibiotics, heavy metals, and polycyclic aromatic hydrocarbons contaminations of the composting mixture do not negatively affect the composting process and compost quality [87–89]. Nevertheless, the actual knowledge is still limited to the investigation of limited classes of mycotoxins (mainly aflatoxins) and small-scale experiments. Although the potential for nutrients' recovery from mycotoxin-contaminated products through composting appears evident, deeper studies are needed to up-scale this treatment.

4.3.2. Mycotoxins' Fate during Composting

The fate of mycotoxins during the composting of contaminated products was assessed to understand whether aerobic biological treatments can represent a suitable strategy for decontamination.

As already described for AD, a reduction in mycotoxins' concentration during composting is expected, since natural composting microorganisms were reported to efficiently degrade some classes of mycotoxins (e.g., aflatoxins) [90]. For instance, fungi (*Armillariella tabescens*) and bacteria (*Pseudomonas putida*) species can degrade AFB1 into less toxic metabolites (aflatoxin D and dihydrodiol-derivates) through two different pathways: (1) modification of the difuran ring and (2) modification of the coumarin structure. Recently, the effective degradation of AFB1 using a thermophilic microbial consortium extracted from compost produced from agricultural wastes was described by Wang et al. [91]. They observed a 95% degradation of AFB1, with an optimal temperature of 55–60 °C and an optimal pH of 8–10. Moreover, the thermophilic microbial consortium exhibited the tolerance to high doses of AFB1 (up to 5000 μg L^{-1}) and extreme heat.

The literature review confirmed that aflatoxins are effectively degraded by composting microorganisms, and aflatoxins' removal is comparable to the one reported for AD (Table 5). Akoto et al. [83] reported a 58.6, 54.5, 96.6, and 83.3% removal for AFB1, AFB2, AFG1, and AFG2, respectively, after the laboratory scale composting of contaminated peanut meal. When contaminated peanut by-products were composted in a pilot scale composting pile, 77% of removal was observed for the total aflatoxins.

The pilot scale co-composting of AFB1-contaminated corn grain with pig slurry or the organic fraction of municipal solid wastes reduced the AFB1 content from 13.04 μg kg^{-1} AFB1 and 12.20 μg kg^{-1} AFB1 to 0.35 μg kg^{-1} AFB1 and 1.75 μg kg^{-1} AFB1, respectively [82]. The average AFB1 removal was 91.5%, a remarkable result that was probably related to the synergic effects of several decontamination agents (microbial activities, high temperature during the active phase, high ammonium-N concentration, and light irradiation).

Composting has already been reported to be an effective biological treatment for organic contaminants' reduction in organic wastes [61]. For instance, Cucina et al. [87] reported that the antibiotic daptomycin was degraded during co-composting through a protease-mediated mechanism. Similarly, extracellular enzymes produced by composting microorganisms may hydrolyze mycotoxins, making their mineralization easier.

Differently from aflatoxins, Ochratoxin A (OTA) increased steadily with the progress of the composting process of coffee pulp and husk, alone or in combination, in naturally and artificially contaminated compost [84]. Authors explained the increase in OTA content with the presence of OTA-producing fungi such as *Aspergillus* spp. section *Nigri*. Since this represents the only report on the OTA fate during composting, further studies are needed to assess whether composting can reduce OTA contamination.

As reported for AD, the literature has not yet evaluated whether mycotoxins removal at the end of composting is due to mineralization or other mechanisms (e.g., binding to cell walls or transformation to other compounds). This aspect should be evaluated in depth to ensure that the compost obtained from mycotoxin-contaminated products is safe and free from toxic compounds.

5. Research Gaps and Future Challenges in Mycotoxins' Degradation through Biological Treatments

Although the literature review highlighted the potential for energy and nutrients' recovery from mycotoxin-contaminated products through AD and composting, this topic is still not sufficiently explored, and several issues should be assessed in order to consider these technologies for real application.

AD and composting can effectively remove mycotoxins, but the removal efficiency depends mainly on mycotoxin-characteristics and process conditions. At this moment, the literature has not yet explored the pathways of mycotoxins' degradation and, consequently, mycotoxin residues can remain in digestate and compost, as well as their metabolites. Future research should focus on the study of mycotoxin degradation mechanisms during biological treatments, to highlight whether these compounds are effectively mineralized to CO_2 and H_2O, converted to less or more toxic metabolites, or only bind to organic structures. On the other hand, the fate of mycotoxin residues in soil after digestate or compost reuse has yet to be evaluated. It is known that soil microorganisms can effectively degrade aflatoxins [92,93] and this could allow digestate and compost utilization in soil even when traces of mycotoxins are present. In addition, the presence of mycotoxin metabolites may not raise major concerns of soil contamination since (i) they are usually less toxic than the original molecules and (ii) because the compost application to the soil is proved to improve the biodegradation of organic pollutants in soil (i.e., compost acts as a source of superbioaugmentation with diverse kinds of microbes and its nutrients help in the biostimulation of these microbes to degrade xenobiotics) [93].

The integration of AD and digestate composting could represent a feasible strategy to enhance mycotoxins' degradation and obtain safe products to be used in agriculture as fertilizers, meeting the Circular Economy principles [94]. Anaerobic and aerobic microbial consortia are completely different and the switch from a reductive environment to an oxidative one might promote different degradative mechanisms, leading to a more efficient mycotoxin removal. The effectiveness of the integrated systems for organic contaminants' removal was already described in the literature [62,87] and, consequently, there is a need to evaluate the effects of coupled AD-composting on mycotoxins' fate. In addition, digestate composting is often recognized as a suitable solution to increase the agronomic potential of digestate due to the improved organic matter stabilization, phytotoxicity removal, and moisture reduction [95–97]. Only recently, Cucina et al. [98] have reported a first assessment of the integrated anaerobic–aerobic treatment of AFB1-contaminated corn. In this first study, a complete (100% w/w) removal of the mycotoxin from the organic matrix was observed, and no traces of the common metabolites were found in the compost. According to the authors, the concurrence of different decontamination agents during the integrated anaerobic–aerobic treatment may probably be responsible for the high effectiveness of the mycotoxin removal. Nevertheless, it should be highlighted that further studies were recommended by the authors to clarify (1) the biochemical mechanisms behind the AFB1 removal and (2) the effect of the operational parameters (i.e., seasonal variations on process effectiveness).

Another point that needs to be clarified before applying the biological treatments on a large-scale is the economic impact of this approach. The production of valuable products (i.e., biomethane and compost) may help farmers facing economic losses derived from the impossibility of selling their crop to grain elevators, or to shellers or other handlers. In addition to the loss of crops and feeds storage, regulatory and disposal costs, health care and veterinary care costs, loss of livestock production, monitoring and research activities

for the determination of mycotoxins, and possible loss of human and animal life have to be involved in the total count of economic losses derived by aflatoxin and mycotoxin contamination [99], making the quantification of economic implications an extremely difficult task [16,100].

Di Maria et al. [101] studied the global performances of anaerobic co-digestion and co-composting of AFB1-contaminated corn by a life cycle assessment approach. The major benefits of AD were due to the biogas production, whereas the ones detected for the composting were due to the replacement of the mineral fertilizers. The impact on human health resulted poorly and was influenced by the presence of AFB1 but largely influenced by the direct emissions, due to the use on land of the organic fertilizers. The authors concluded by remarking on the necessity for further research on the integration of AD and composting for the treatment of mycotoxin-contaminated products. In fact, from a life cycle assessment approach, the energy produced from biogas could cover the energy requirements of composting, making the whole recycling treatment sustainable in environmental and economic terms. Indeed, biomethane has a high calorific value and can be used to produce heat and electricity to be used for internal consumption, making the disposal system energetically independent. This could be a clear advantage in the energetic crisis scenario that we are facing nowadays. Economically speaking, biomethane value, which depends on the substrate and plant size, is estimated to range from 0.5 \$US/m^3 (4.7 cent \$US/kWh) to 1.5 \$US/m^3 (15 cent \$US/kWh) [102]. Even if the economic value of compost is negligible, it still represents a potential income for farmers that may help in facing economic losses due to mycotoxin contamination. Furthermore, compost value is expected to increase due to the scarcity of raw materials used to produce synthetic mineral fertilizers, of which the cost is rapidly increasing.

Once the technical feasibility of energy and nutrients' recovery from mycotoxin-contaminated products is completely defined, an update of fertilizer legislation would be mandatory. At this date, there are no national and international regulations that allow the spreading of organic fertilizers obtained through biological treatments from mycotoxin-contaminated biomasses.

A last major concern is represented by the potentially increased workers' exposure to mycotoxins in waste recycling and recovery facilities. Indeed, human health risks related to biological and chemical agents are already recognized in domestic waste composting facilities (e.g., endotoxins, volatile organic compounds) [103]. Although the health risk assessment approaches described by Schlosser et al. [104] did not suggest a significant threat to the workers' health related to mycotoxins in five facilities treating wastes, the management of mycotoxin-contaminated products would certainly require a careful evaluation of the occupational exposure to these dangerous contaminants.

6. Conclusions

This literature review, conducted on the recovery of energy and nutrients from mycotoxin-contaminated food products through biological treatments, highlighted the potential of anaerobic digestion and composting for the decontamination and valorization of these wastes. First, neither the anaerobic nor the aerobic biological treatment were affected by the contamination, resulting in well performing processes (i.e., high biogas yields and high-quality compost production). Secondly, variable mycotoxin removals can be obtained, which depend mostly on the operational parameters of the process and on the type of mycotoxin.

Although the potential of these strategies for the valorization of contaminated products in the frame of Circular Economy is evident, future research is needed to fill the knowledge gaps emerged during the conducted literature review. Starting from the need to study the pathways of mycotoxins' removal during biological treatments, it will be mandatory to assess the fate of mycotoxins' residues and metabolites in soil following the agricultural reuse of digestate and compost derived from contaminated feedstock. Enhancing the environmental and economical sustainability of the approach, i.e., through the integration

of anaerobic and aerobic processes or through the optimization of anaerobic digestion, are other objectives that scientists should address to favor the large-scale application of biological processes for the treatment of mycotoxin-contaminated products.

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