IJM - Italian Journal of Mycology
ISSN 2531-7342 - Vol. 54 (2025): 41 - 63
Journal homepage: https://italianmycology.unibo.it/

*Review*

# Historical data on fungal contamination of maize (*Zea mays* L.) from different agroecological zones in Nigeria: a review

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ARTICLE INFO
Received 16/08/2024; accepted 21/01/2025
https://doi.org/10.6092/issn.2531-7342/20210

**Abstract**
Fungi attack maize in the field, and if warm and humid conditions that are suitable for fungal growth and mycotoxin production prevail, they can grow rapidly during storage, causing loss of quantity and quality, a reduction in nutrient content, and mycotoxin production in the crop. Most of the world's maize is lost to disease during storage, especially in developing countries. The three main genera that flourish in warm regions such as Nigeria and produce mycotoxins are *Fusarium*, *Penicillium* and *Aspergillus*. In this review, only 34 publications on the fungal contamination of maize from five agroecological zones of Nigeria where maize is grown were found and used for the study. The results of these works revealed that 39 different fungal genera comprising 36 and 3 genera of moulds and yeasts, respectively, are the major mycological contaminants of maize in Nigeria. The most common types of mould were *Aspergillus* spp. with an occurrence frequency of 37.31%, *Fusarium* spp. (23.13%), *Penicillium* spp. (13.76%), *Rhizopus* spp. (5.43%), *Mucor* spp. (4.71%), *Botryodiplodia* spp. (1.44%), *Cladosporium* spp. (1.44%), and *Curvularia* spp. (1.08%). Mould contamination was more prevalent in farm samples (39.49%) than in market (33.12%) and storage (27.49%) samples. This review revealed that there has been an upsurge of new fungal species that contaminate the maize consumed in Nigeria during the last decade. The reported presence of many harmful toxigenic fungi in this work, which presents the maize fungal pathogens from different agroecological zones of Nigeria since 1960, raises serious concerns with respect to postharvest losses, food insecurity, and public health.

Key words: agroecological zones, *Aspergillus*, *Fusarium*, mycotoxins, maize, *Penicillium*

## Introduction

Maize is one of the most important crops in the world. It is consumed as a staple food in Nigeria, accounting for approximately 43% of the calories in the average Nigerian diet (Adiaha, 2018). Many studies on maize yield have shown that productivity has increased in all agroecological areas of the country. The country produces 12,948,920 tons, covering approximately 6.5 million hectares of land (FAOSTAT, 2022). Maize is used to make “koko” or “ogi” (a traditional fermented paste) and to make “tuwo” (a hard porridge or dough), which is common in the northern and central regions. Corn, as it also called, is roasted or boiled as a snack during the harvest season (Muhammad et al., 2019). However, this highly consumed crop is susceptible to fungal and mycotoxin contamination. Several studies have demonstrated the susceptibility of Nigerian maize to fungi and mycotoxins (Muhammad et al., 2019; Kolawole et al., 2020; Ezekiel et al., 2021; Mabekoje et al., 2023). The major fungal genera associated with food spoilage, including maize-based food and feed, are *Aspergillus*, *Penicillium*, and *Fusarium* (Adeyeye, 2016). Many species of fungi are considered foodborne pathogens because they exist in all conditions and can thrive in various environments. Unlike many other microbial pathogens, fungal species are opportunistic and can colonize and grow in almost any type of food. These pathogens are thought to enter food processing facilities mostly through contaminated food and feed ingredients (Magomya and Mbatsav, 2023). Food spoilage due to fungal diseases causes enormous losses worldwide every year (Faizan et al., 2019). Fungal diseases affecting wheat, maize, and rice cause annual losses of an estimated $60 billion in global agriculture (Varsha and Nampoothiri, 2016).

The attack of plants by various fungi not only causes a reduction in crop yield and quality, with significant economic losses but also contaminates grains with poisonous fungal secondary metabolites called mycotoxins. The ingestion of such mycotoxin-contaminated grains has enormous public health significance because these toxins can cause diseases in humans and animals (Bhat and Vasanthi, 2003). Of greatest concern is the relevance of these toxins in human hepatoma and oesophageal cancer (Shephard, 2008). There are hundreds of mycotoxins, but the ones that have the greatest impact on agriculture and public health, particularly in the tropics where Nigeria is situated, include aflatoxins, fumonisins, ochratoxins, zearalenone, and deoxynivalenol. Aflatoxins, particularly the potent $AFB_1$, are hepatocarcinogens, whereas fumonisins are associated with human oesophageal cancer. Ochratoxins cause kidney impairment in humans, whereas zearalenone is an infertility toxin, and deoxynivalenol causes intestinal hemorrhage and immunosuppression (Zain, 2011).

Mycotoxins are frequently detected in many foods, including maize (Adeyeye, 2016; Perczak et al., 2018). Approximately 25% of maize and maize products worldwide contain different types of mycotoxins, making mycotoxins a global food safety and public health problem (Chilaka et al., 2017). An estimated 4.5 billion people in developing countries are exposed to aflatoxins through contaminated food (CDC, 2004). In addition to their adverse effects on public health, mycotoxins cause economic losses due to mycotoxin-induced reductions in animals and plants productivity. The Food and Agriculture Organization (FAO) estimates that 25% of food crops worldwide are severely contaminated by mycotoxins during cultivation or storage (USDA, 2016). In Nigeria, poor agricultural practices at harvest time, combined with the country's humid climate, lead to rapid mould growth and mycotoxin production with heavy economic losses. This is evident in the fact that between 2007 and 2016, there were rejections of Nigerian production at EU borders due to the aflatoxin level, which culminated in the imposition of an import ban restricting the export of five major agricultural products from Nigeria to any European Union member country. This ban caused a decline of ₦ 671.1 billion or 34.6% in food trade, including both raw agricultural commodities and processed food items such as grains, fruits, and vegetables (Imade et al., 2021). Therefore, this review aims to elucidate the fungal profile of maize grown in all agroecological zones of Nigeria with the goal of understanding the impact of climate and associated health implications of fungal incidence in maize in Nigeria.

## 1. Historical data on fungal contamination of maize from five agroecological zones in Nigeria

Nigeria is a country known for its diverse culture and services. Agroecological diversity is one of its most valuable but often neglected features. Agroecological zones promote agriculture, putting farmers and communities in the driver's seat. Fig. 1 below shows the locations of each agroecological zone in Nigeria.

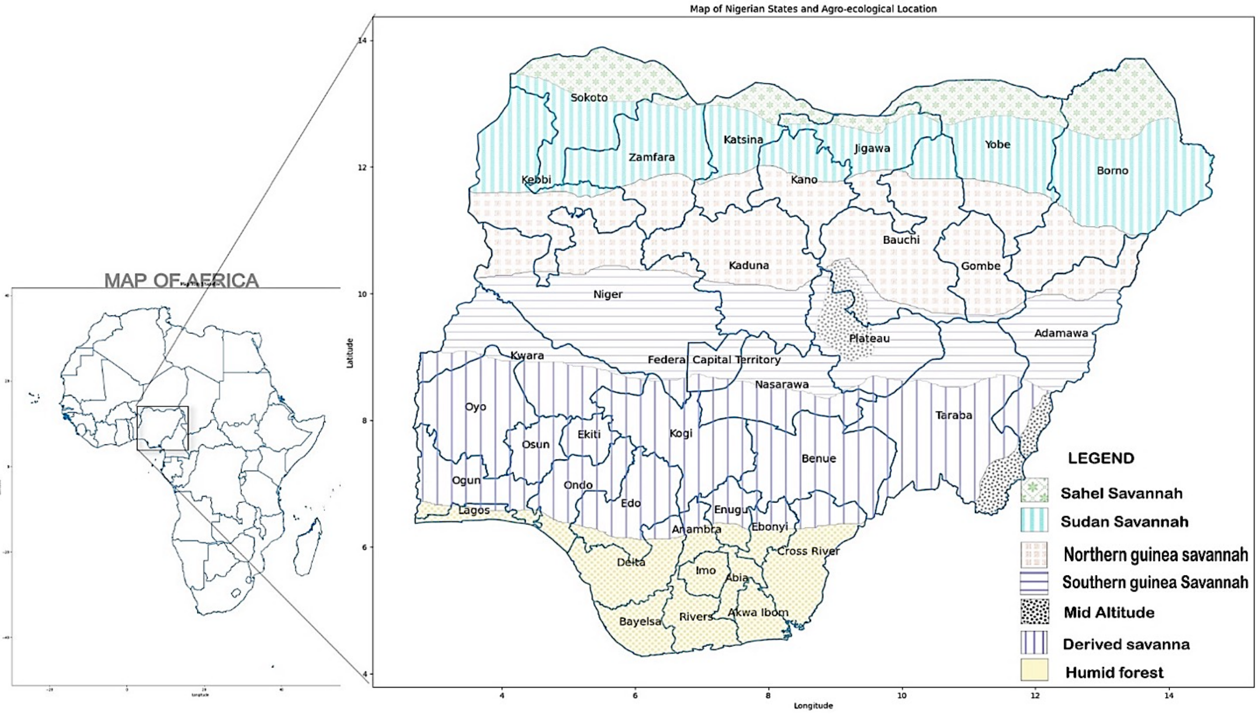


**Fig. 1 –** Presentation of different agroecological zones of Nigeria

There are seven agroecological zones in Nigeria, namely, the Derived Savanna (DS), Southern Guinea Savanna (SGS), Northern Guinea Savanna (NGS), Medium Altitude Area (MA), Sudan Savanna (SS), Sahel Savanna (SHS) and Humid Forest (HF).

Okafor (1966; 1968) recorded mesophilic fungi such as *Fusarium moniliforme* J. Sheld. *Aspergillus flavus* Link, and *Rhizopus arrhizus* A. Fisch. and thermophilic fungi such as *Thermomyces lanuginosus* Tsikl., *Mucor pusillus* Lindt, and *Rhizomucor* sp. deteriorating a stack of maize in Edo-Ekiti in DS. Broadbent (1967, 1969) and Oyeniran (1973a, b) performed extensive works on the postharvest deterioration of maize in Ibadan, which is located in the DS. They isolated and identified 30 moulds from damaged crops. The grains were improperly dried and stored in conditions where they could absorb moisture. The species found were *Absidia corymbifera* Sacc. & Trotter, *Aspergillus chevalieri* Thom & Church, *Aspergillus melleus* Yukawa, *Aspergillus penicilloides* (Wehmer), *Botryodiplodia theobromae* Pat, *M. pusillus* Lindt, *Paecilomyces varioti*

Bainier, *Penicillium decumbens* Thom, *Penicillium steckii* K.W. Zaleski, *Penicillium variabile* Sopp, and *Syncephalastrum racemosum* Cohn ex J. Schröt. Umechuruba (1986) investigated the effect of sulfur on seed yield in diseases associated with different maize varieties in eastern Nigeria. The maize varieties Fraz 23 and Fraz 34 were obtained from the National Cereals Research Institute, Amakama, Umuahia, SGS. The variety Bendel White was obtained from Rivers State in the HF. He reported that kernels from the three different corn varieties (Fraz 23, Fraz 34, and Bendel White) were contaminated with fungi during the harvest seasons of 1982 and 1983. The effects of the seed coating chemical thiols (e.g., 25% heptachlor and 25% tetramethylthiuram disulfide (TMTD)) on fungal and grain viability were also investigated. The three types of screened maize varieties were found to have kernels containing *A. flavus*, *F. moniliforme*, *F. nivale* Ces. ex Berl. & Voglino, *F. semitectum* Berk. & Ravenel, *Penicillium oxalicum* Currie & Thom, *Saccharomyces* spp., *Rhizopus* spp., and *Curvularia pallescens* Boedijn at notably high percentages. Adisa (1994) examined the effects of mould contamination of two cereals, wheat and maize, collected from Kaduna (NGS), Zaria (SS), Jos (NGS), Ibadan (DS) and Lagos (HF) in Nigeria. She isolated thirteen fungi from both maize and wheat. Some of the species included *Helminthosporiurn turcicum* Pass, *Mucor sexualis* G. Sm, *Penicillium dupontii* Griffon & Maubl, *Penicillium luteum* Zukal, *Penicillium wortmannii* G.P.Shukla, *Rhizopus oryzae* Went & Prins. Geerl, and *Rhizopus stolonifera* Vuill. Adebajo et al. (1994) conducted a second study in the same year on the production of mycotoxins and microbial communities in maize and corn snacks in southwestern states of Nigeria belonging to the DS and SGS agroecological zones. They identified 31 fungal species belonging to 11 genera: *Aspergillus* spp., *Penicillium* spp., *Fusarium* spp., *Rhizopus* spp., *Mucor* spp., *Chaetomium* spp., *Cladosporium* spp., *Thermoascus* spp., *Acremonium* spp. *Scopulariopsis* spp., *Syncephalastrum* spp.

Bankole (1994) examined moisture content, fungal diseases, and kernel germination during long-term corn storage. He demonstrated that *Alternaria alternata* (Fr.) Keissl, *Botryodiplodia theobromae*, *Fusarium* spp., and *Macrophomina phaseolina* (Tassi) Goid, were the most common fungi at harvest and then they were replaced by storage fungi, primarily *Aspergillus* spp. and *Penicillium* spp. Opadokun and Ikeorah (1983) isolated several species of *Aspergillus*, *Penicillium*, *Cladosporium*, *Alternaria*, *Fusarium*, and *Acremonium* from maize samples from Kano (NGS and SGS) and Plateau (NGS). In 1994, Aja-Nwachukwu and Emejuaiwe isolated the same species from Aba (HF), Abakaliki (DS), Afikpo (SGS), Okigwe, and Owerri in southern Nigeria. The corn samples contained twelve different mould species belonging to the same group. Ekpo and Banjoko (1994) isolated *Aspergillus* spp., *Fusarium* spp., *Curvularia* spp., *Drechslera* spp., *Penicillium* spp., and *Rhizopus* spp. from maize seeds in their study.

Owalade et al. (2001) identified seed-borne pathogens in maize from a farm in Ibadan (DS). They reported that the fungi isolated included *Fusarium* sp., *Drechsiera* sp., *Botryopdiplodia* sp., *Cephalosporium* sp., and *Collectrocrichum* sp. Other field fungi included *Curvularia lunata* (Wakker) Boedijn, *Fusarium semitectum* and *Nigrospora oryzae* (Berk. & Broome) Petch. The fungi isolated from stored maize were *Aspergillus* spp. and *Fusarium* spp.

Bankole et al. (2003) conducted a study in 2000 to determine the prevalence of *Fusarium* spp. and $FB_1$ contamination in maize from farms and markets in eight districts of Ogun State (SGS), Nigeria. *Fusarium* contamination was detected in 85% of the 92 samples. The species included *F. oxysporum* sensu Smith & Swingle, *F. moniliforme*, *F. solani* (Mart.) Sacc, *F. graminearum* Schwabe, and *F. pallidoroseum* (Cooke) Sacc. In another study, Bankole and Mabekoje (2004) reported aflatoxin and fumonisin in maize grown in western Nigeria in the HF agroecological zone. They discovered the following species of fungi: *Fusarium* sp., *Rhizopus* sp., *Mucor* sp., *Nigrospora* spp., *Aspergillus* spp., *Curvularia* sp., *Penicillium* sp., and *Cladosporium* sp.

In a humid tropical environment (Imo state), Okoli et al. (2007) isolated the microflora of poultry feed raw materials. They reported that maize was contaminated by *Aspergillus* sp. and *Mucor* sp. Adejumo et al. (2007a) conducted a study in four southwestern Nigerian states, comprising Ondo (NGS, SGS and DS), Ekiti (SGS), Osun (SGS), and Oyo (NGS and SGS), to determine the presence of *Fusarium* mycotoxins in maize intended for human consumption. *Fusarium verticillioides* (Sacc.) Nirenberg was the most common pathogen isolated from maize seeds, accounting for 70% of all pathogens. The other 30% of the isolates were *F. equiseti* (Corda) Sacc, *F. sporotrichioides* Sherb, *F. graminearum*, *F. pallidoroseum*, *F. compactum* (Wollenw.) Raf, *F. proliferatum* (Matsush.) Nirenberg, and *F. subglutinans* (Wollenw. & Reinking) P.E. Nelson, Toussoun & Marasas. Adejumo et al. (2007b) reported the presence of 10 *Fusarium* species on maize in another study conducted that same year in the previous locations. Atehnkeng et al. (2008) collected maize samples during research in three agroecological zones in Nigeria to determine the distribution and aflatoxin production capacity of the *Aspergillus* genus section Flavi. Five fungal genera were detected in the corn samples collected during the research: *Aspergillus*, *Fusarium*, *Penicillium*, *Trichoderma*, and *Macrosporum*. *Aspergillus* genus was the most common pathogen in all areas. *Fusarium* and *Macrosporum* genera were the second most common, whereas *Trichoderma* and *Penicillium* were the least common. The incidence of *Aspergillus* species varied by district, with Bida in SGS having the greatest occurrence and Zaria in NGS having the lowest. In Southwest Nigeria, Ezekiel et al. (2008) investigated the frequency of *Fusarium* species in commercial corn in 5 states, namely, Lagos (HF), Ogun (SGS and HF), Ondo (SGS, NGS, and DS), Osun (SGS), and Ekiti (SGS). These findings revealed a total of 183 isolates, and *F. sporotrichioides* had the highest rate with a 96% isolation frequency.

Perrone et al. (2014) examined aflatoxin production in maize in Ghana and Nigeria and the cluster structure of *Aspergillus* section Flavi, whose members were present in 42 of 56 commercial samples and 21 of 35 farm samples. The contamination incidence (percentage of infected kernels) in the market and farm samples varied, with a mean of 21% for both types of samples and a median of 11.5% and 16%, respectively. After *Aspergillus flavus* (98.5%), *Aspergillus tamarii* Kita (1.4%) was the second most common isolated species. Additionally, *Aspergillus flavofurcatus* Bat. & H. Maia (sister species to *Aspergillus tamarii*) was found from Ikenne, which belongs to the HF agroecological zone, and *Aspergillus parvisclerotigenus* (Mich. Saito & Tsuruta) Frisvad & Samson from Mokwa, which belongs to the SGS agroecological zone.

In Afikpo (SGS agroecological zone), Ebonyi State, Egwurochi et al. (2015) sought to isolate and identify fungi associated with maize grain storage. Five distinct genera of fungi were identified from the gathered samples: *Mucor* spp., *Rhizopus* spp., *Fusarium* spp., *Aspergillus* spp., *Penicillium* spp. In Osun State, Akande et al. (2017) conducted a study on screening fungi and chemicals from maize at open markets. The results revealed that the fungal total counts ranged from $1.50 \times 10^5$ to $2.1 \times 10^7$ CFU/g. Among the toxigenic fungi, 12 species were identified; the most common genus was *Aspergillus* (85.7%), followed by *Fusarium* and *Penicillium* (14.3%).

The moulds found in dried maize samples were investigated by Jeff-Agboola and Omosanyin (2017) in Okitipupa (DS), a local government in Ondo State (DS). The most common mould species were *Penicillium otrametous* Samson & W. Gams, *Fusarium oxysporum*, *Fusarium proliferatum*, *Aspergillus flavus*, *Aspergillus tamarii*, *Aspergillus niger* Tiegh, *Aspergillus fumigatus* Fresen, and *Aspergillus terreus* Thom. Keta et al. (2019) evaluated the aflatoxin levels of millet and maize cereal grains and the occurrence of fungal species in the Guinea savanna zones of Kebbi state (SS). The state is characterized by Sudan and Guinea savanna vegetation and a minimum temperature of 21 – 24 °C, with a relative humidity range of 17 – 80%. Eight fungal species were isolated and identified and *A. flavus* had the highest incidence among the fungi, accounting for 30.9% of the total species.

Muhammad et al. (2019) investigated the presence of diseases in maize collected from fields, stores, and markets in 25 local governments in Niger State (NGS and SGS). The most prevalent fungi from the state's agroecological zones were *Aspergillus* spp., *Rhizopus* spp., and *Mucor* spp., whereas yeast and *Penicillium* spp. were the least prevalent. *Aspergillus* species were most common in the wet, driest, wettest, and dry zones. The market samples presented the highest frequency of fungal incidence, followed by the storage and field samples. Oyeka et al. (2019) evaluated mycotoxin occurrence in 36 maize samples sold at local markets in Anambra State (SGS and HF) and isolated mycotoxin-producing products. To assess mycotoxins, twelve randomly selected blended samples were used to isolate 292 fungal isolates, which included 20 species of mould and 7 species of yeast. The new species identified were *Cunninghamella eleganz* Lendner, *Verticillium* sp., *Scedosporium prolificans* (Hennebert & B.G. Desai) E. Guého & de Hoog, *Alternaria infectoria* E.G. Simmons, *Fonsecaea pedrosoi* (Brumpt) Negroni, *Malbranchae* sp. and *Cladosporium carrionii* Trejos. Shehu et al. (2020) evaluated mould and mycotoxin contamination in maize stored in Kebbi State (SS). The fungi that were isolated included *Penicillium notatum* Westling, *Fusarium moniliforme*, *Fusarium graminearum*, *Fusarium verticillioides*, *Aspergillus flavus*, *Aspergillus niger*, *Aspergillus fumigatus*, and *Aspergillus parasiticus* Speare.

A study by Mubarak and Keta (2021) of fungi on stored maize in Kebbi State (SS) revealed the presence of *Fusarium* sp., *Ceplosporium* sp., *Aspergillus* sp., *Penicillium* sp., *Mucor* sp. Dabara (2021) isolated moulds from maize and sorghum in microclimatic zones of Niger State (NGS). The samples of maize from each zone of the study contained the following *Penicillium* species: *P. griseofulvum* Dierckx had an incidence of 16.6% in both the wettest and driest zones, while *P. chrysogenum* Thom had an incidence of 25% in both these zones as well. In contrast, *P. verrucosum* Dierckx exhibited an incidence of 58.3%, which was the highest observed in the wettest zone. *Penicillium chrysogenum* had the lowest incidence in the driest zone, and *P. verrucosom* had the highest incidence in the moist zone. Badmos (2021) conducted a study on the *Fusarium* and mycotoxin profiles of sorghum and maize grown in Niger State (NGS). *Fusarium verticillioides* was the most frequent species in sorghum and maize with 59.38%, whereas *F. oxysporum* was the least frequent species with only 7.8%. Ekpakpale et al. (2021) researched the species diversity of filamentous fungi in maize grown in Ondo State and discovered the new species *Lichtheimia ramosa* (Zopf) Vuill, *A. brasiliensis* Varga, Frisvad & Samson, *Penicillium cinamopupureum* S.Abe ex Udagawa, *A. tritici* B.S. Mehrotra & M. Basu, and *Talaromyces sayulitensis* Visagie, N. Yilmaz, Seifert & Samson.

Abdulrazak et al. (2022) conducted a study on the fungal spoilage of stored maize in two markets in Lagos State (HF). Samples of maize were taken from both the Almabamba and Igando markets, and four genera were isolated: *Fusarium*, *Aspergillus*, *Penicillium* and *Rhizopus*. These results showed that *A. niger* was the most predominant and that *Penicillium* sp. was the least predominant among the isolated fungi.

**Table 1 –** Fungi in the derived savanna (DS) with values between brackets representing the % of occurrence of the isolates.

| Year | Fungi | References |
|---|---|---|
| 1966 | *Fusarium moniliforme*, *Aspergillus flavus*, *Rhizopus arrhizus*, *Thermomyces lanuginosus*, *Mucor pusillus*, *Rhizomucor* sp. | Okafor (1966) |
| 1967 | *Absidia corymbifera*, *Aspergillus candidus*, *A. chevalieri*, *A. flavus*, *A. fumigatus*, *A. melleus*, *A. niger*, *A. penicilloides*, *A. tamarii*, *A. terreus*, *A. versicolor*, *Botryodiplodia theobromae*, *Fusarium moniliforme*, *Mucor pusillus*, *Paecilomyces varioti*, *Penicillium citrinum*, *P. decumbens*, *P. steckii*, *P. variabile*, *Rhizopus arrhizus*, *Syncephalastrum racemosum* | Broadbent (1967) |
| 1968 | *Fusarium moniliforme*, *Aspergillus flavus*, *Rhizopus arrhizus*, *Thermomyces lanuginosus*, *Mucor pusillus*, *Rhizomucor* sp. | Okafor (1968) |
| 1969 | *Absidia corymbifera*, *Aspergillus candidus*, *A. chevalieri*, *A. flavus*, *A. fumigatus*, *A. melleus*, *A. niger*, *A. penicilloides*, *A. tamarii*, *A. terreus*, *A. versicolor*, *Botryodiplodia theobromae*, *Fusarium moniliforme*, *Mucor pusillus*, *Paecilomyces varioti*, *Penicillium citrinum*, *P. decumbens*, *P. steckii*, *P. variabile*, *Rhizopus arrhizus*, *Syncephalastrum racemosum* | Broadbent (1969) |
| 1973 | *Absidia corymbifera*, *Aspergillus candidus*, *A. chevalieri*, *A. flavus*, *A. fumigatus*, *A. melleus*, *A. niger*, *A. penicilloides*, *A. tamarii*, *A. terreus*, *A. versicolor*, *Botryodiplodia theobromae*, *Fusarium moniliforme*, *Mucor pusillus*, *Paecilomyces varioti*, *Penicillium citrinum*, *P. decumbens*, *P. steckii*, *P. variabile*, *Rhizopus arrhizus*, *Syncephalastrum racemosum* | Oyeniran (1973a,b) |
| 1983 | *Aspergillus* spp., *Penicillium* spp., *Cladosporium* spp., *Alternaria* spp., *Fusarium* spp., *Acremonium* spp. | Opadokun and Ikeorah (1983) |
| 1994 | *Aspergillus clavatus* (10.3%), *A. flavus* (11.6%), *A. fumigatus* (24.6%), *A. nidulans* (24.6%), *A. niger* (9.3%), *Fusarium moniliforme* (2%), *Helminthosporiurn turcicum* (5.2%), *Mucor sexualis* (4.6%) *Penicilliurn dupontii* 4.8%), *P. luteum* (1.4%), *P. wortmannii* (1.6%), *Rhizopus oryzae* (20%), *R. stolonifera* (24%) | Adisa (1994) |
| 2001 | *Fusarium moniliforme*, *F. semitectum*, *Drechsiera maydis*, *Botryopdiplodia theobromae*, *Cephalosporium acremonium*, *Collectrocrichum graminicola*, *Curvularia lunata*, *Nigrospora oryzae*, *Aspergillus* spp., *Fusarium* spp. | Owalade et al. (2001) |
| 2008 | *Aspergillus* sp. (70.4%), *Fusarium* sp. (24.4%), *Penicillium* sp. (0.7%) *Trichoderma* sp. (0.4%), *Macrophominia* sp. (15.4%) | Atehnkeng et al. (2008) |
| 2017 | *Aspergillus flavus* (40%), *A. tamarii* (20%), *A. niger* (4%), *A. fumigatus* (4%), *A. terreus* (4%), *Fusarium oxysporum* (12%), *F. proliferatum* (16%), *Penicillium otrametous* (4%) | Jeff-Agboola and Omosanyin (2017) |
| 2021 | *Aspergillus aflatoxiformans* (4%), *A. neoniger* (58%), *A. brasiliensis* (5%), *A. welwitschia* (75%), *A. fischeri*, *A. fumigatus*, *A. terreus* (72%), *A. flavus* (56%), *A. tamarii* (71%), *A. pseudonomiae* (60%), *A. tritici* (73%), *A. brasiliensis* (5%), *Lichtheimia romosa* (76%) *Penicillium cinamopupureum* (77%), *Talaromyces savulitensis* (100%) | Ekpakpale et al. (2021) |
| 2022 | *Fusarium verticillioides*, *Aspergillus flavus*, *A. niger*, *Botryodiplodia theobromae* | Adetayo et al. (2022) |

**Table 2 –** Fungi in southern Guinea savanna (SGS) with values between brackets representing the % of occurrence of the isolates

| Year | Fungi | References |
|---|---|---|
| 1982 | *Aspergillus flavus* (29.72%), *Fusarium moniliforme* (27.08%, *F. nivale* (6.66%), *F. semitectum* (10.55%), *Penicillium oxalicum* (9.30%), *Saccharomyces* spp. (2.36%), *Rhizopus* spp. (1.38%), *Curvularia pallescens* (0.55%) | Umechuruba (1986) |
| 1983 | *Aspergillus flavus*, *Fusarium moniliforme*, *F. nivale*, *F. semitectum*, *Penicillium oxalicum*, *Saccharomyces* spp., *Rhizopus* spp., *Curvularia pallescens*, *Aspergillus* spp., *Penicillium* spp., *Cladosporium* spp., *Alternaria* spp., *Fusarium* spp., *Acremonium* spp. | Opadokun and Ikeorah (1983) |
| 1994 | *Aspergillus niger* (100%), *A. flavus* (96%), *A. fumigatus* (94%), *A. ochraceus* (38%), *A. chevalieri* (62%), *A. terreus* (38%), *A. candidus* (12%), *A. tamarii* (12%), *A. parasiticus* (18%), *A. nidulans* (4%), *Penicillium citrinum* (80%), *P. chrysogenum* (80%), *P. cyclopium* (46%), *P. funiculosum* (38%), *P. decumbens* (24%), *P. thomii* (18%), *Fusarium monoliforme* (42%), *F. Solani* (36%), *F. oxysporum* (8%), *Rhizopus arrhizus* (48%), *R. homothalicus* (42%), *Mucor pusillus* (36%), *Mucor* sp. (16%), *Chaetomium globosum* (8%), *C. virginicum* (4%), *Cladosporium oxysporum* (4%), *C. herbarum* (2%), *Thermoascus aurantiacus* (2%), *Acremonium* sp. (4%), *Scopulariopsis candida* (2%), *Syncephalastrum racemosum* (4%) | Adebajo et al. (1994) |
| 1994 | *Fusarium* spp., *Macrophomina phaseolina*, *Fusarium semitectum*, *F. pallidoroseum*, *F. monoliforme*, *Curvularia pallenscens*, *C. lunata*, *Drechslera maydis*, *Penicillium* spp., *Rhizopus* spp. | Ekpo and Banjoko (1994) |
| 2000 | *Fusarium oxysporum* (7.40%), *F. moniliforme* (55.55%), *F. solani* (11.11%), *F. graminearum* (25.92%), *F. pallidoroseum* (10.18%), *Fusarium* spp. (9.25%) | Bankole et al. (2003) |
| 2008 | *Aspergillus* sp. (84.4%), *Fusarium* sp. (25.1%), *Penicillium* sp. (0.5%) *Macrophominia* sp. (13.1%) | Atehnkeng et al. (2008) |
| 2014 | *Aspergillus flavus* (98.5%), *A. tamarii* (1.4%) | Perrone et al. (2014) |
| 2015 | *Aspergillus* spp. (33.3%), *Fusarium* spp. (21.4%), *Penicillium* spp. (19.0%), *Rhizopus* spp. (11.9%) | Egwurochi et al. (2015) |
| 2017 | *Aspergillus flavus* (83.3%), *A. glaucus* (66.7%), *A. fumigtus* (16.7%), *A. niger* (33.3%) *A. parasiticus* (16.7%), *Botrytis* spp. (33.3%), *Fusarium proliferatum* (16.7%), *F. oxysporum* (16.7%), *Penicillium* spp. (16.7%), *Rhizopus stolonifera* (83.3%), *Scopulariopsis brevicaulis* (16.7%), *Trichoderma* spp. (33.3%) | Akande et al. (2017) |
| 2019 | *Aspergillus niger* (36), *A. ochraceus* (22), *A. flavus* (30.8), *A. fumigatus* (25), *A. parasiticus* (23), *Mucor* spp. *(16.2)*, *Fusarium* spp. (22.2), *Penicillium* spp. (25), *Saccharomyces* spp. (25), *Rhizopus* spp. (34.1) | Muhammad et al. (2019) |
| 2023 | *Aspergillus clavatus* (8), *A. flavus* (32%), *A. niger* (32%), *A. fumigatus* (24%), *A. ochraceus* (8%), *Curvularia lunata* (8%), *Penicillium chrysogenum* (12%), *P. citrinum* (8%), *Fusarium graminearum* (24%), *F. pallidoroseum* (8%), *F. verticillioides* (80%), *F. solani* (12%), *Rhizopus* spp. (20%), *Mucor* spp. (20%) | Mabekoje et al. (2023) |

*Fusarium verticillioides* was found in maize sold at certain markets in the Nigerian metropolis of Ibadan (DS), according to Adetayo et al. (2022). The findings revealed that fungal infections caused more than 50% of the evaluated seeds to germinate. The maize samples taken from the Apata market presented the greatest fungal infection rate (28.2%), whereas the samples taken from the Bodija market presented the lowest fungal infection rate (22.3%). Furthermore, *Fusarium verticillioides*, *Aspergillus flavus*, *Aspergillus niger*, and *Botryodiplodia theobroma* Pat, were among the discovered fungal isolates. Mabekoje et al. (2023) investigated the fumonisin content of maize grains collected from Nigerian agroecological zones (HF, NGS, SGS, and SS). The fungal species frequently isolated across all agroecological zones were *A. niger*, *A. fumigatus*, *A. ochraceus* G. Wilh, *Penicillium chrysogenum*, *P. citrinum* Thom, *P. pinophilum* Hedgc., *Fusarium graminearum*, *F. pallidoroseum* (Cooke) Sacc, *F. verticillioides*, *F. solani*, *Rhizopus* spp., and *Mucor* spp. Tables 1 to 5 show the fungal profiles isolated in each agroecological zone.

**Table 3 –** Fungi in northern Guinea savanna (NGS) with values between brackets representing the % of occurrence of the isolates.

| Year | Fungi | References |
|---|---|---|
| 1983 | *Aspergillus* spp., *Penicillium* spp., *Cladosporium* spp., *Alternaria* spp., *Fusarium* spp., *Acremonium* spp. | Opadokun and Ikeorah (1983) |
| 1994 | *Aapergillus clavatus*, *A. flavus*, *A. fumigatus*, *A. nidulans*, *A. niger*, *Fusarium moniliforme*, *Helminthosporium turcicum*, *Mucor sexuaalis*, *Penicillium dupontii*, *P. luteum*, *P. wortmannii*, *Rhizopus oryzae*, *R. stolonifera* | Ekpo and Banjoko (1994) |
| 1994 | *Fusarium semitectum*, *F. pallidoroseum*, *F. monoliforme*, *Curvularia pallenscens*, *C. lunata*, *Drechslera maydis*, *Penicillium* spp., *Rhizopus* spp. | Adisa (1994) |
| 2007 | *Fusarium verticilloides* (70%), *F. equiseti* (9%), *F. sporotrichiodes* (42%), *F. graminearum* (30%), *F. pallidoroseum* (15%), *F. compactum* (12%), *F. proliferatum*, *F. subglutinans* (4%) | Adejumo et al. (2007a) |
| 2007 | *Fusarium verticillioides* (71%), *F. sporotrichioides* (64%), *F. graminearum* (32%), *F. pallidoroseum* (15%), *F. compactum* (12%), *F. equiseti* (9%), *F. acuminatum* (8%), *F. subglutinans* (4%), *F. oxysporum* (1%) | Adejumo et al. (2007b) |
| 2008 | *Aspergillus* sp. (14%) | Atehnkeng et al. *(*2008) |
| 2019 | *Aspergillus niger* (36%), *A. ochraceus* (31%), *A. falvus* (25%), *A. fumigatus* (18.8%), *A. parasiticus* (25%), *Mucor* spp. (24.3%), *Fuarium* spp. (11.1%), *Penicillium* spp. (37.5%), *Saccharomyces* spp. (33.3%), *Rhizopus* spp. (29.3%) | Muhammad et al. (2019) |
| 2021 | *Penicillium verrucosom* (67.78%), *P. chrysogenum* (18.42%), *P. griseofulvum* (15.78%) | Dabara (2021) |
| 2021 | *Fusarium verticilloides* (59.38%), *F. sporotrichioides* (18.96%), *F. graminearium* (18.95%), *F. equiseti* (13.79%), *F. subglutinans* (12.06%), *F. nygamai*, *F. semitectum* (21.27%), *F. solani*, (12.76%) *F. oxysporum* (7.8%) | Badmos (2021) |
| 2023 | *Aspergillus clavatus* (16%), *A. flavus* (24%), *A. nidulans* (12%), *A. niger* (40%), *A. ochraceus* (4%), *Curvularia lunata* (8%), *Penicillium chrysogenum* (8%), *Fusarium graminearum* (12%), *F. pallidoroseum* (20%), *F. verticillioides* (60%), *Rhizopus* spp. (12%), *Mucor* spp. (16%) | Mabekoje et al. (2023) |

**Table 4 –** Fungi in Humid Forest (HF) with values between brackets representing the % of occurrence of the isolates.

| Year | Fungi | References |
|---|---|---|
| 1983 | *Aspergillus* spp., *Penicillium* spp., *Cladosporium* spp., *Alternaria* spp., *Fusarium* spp., *Acremonium* spp. | Opadokun and Ikeorah (1983) |
| 1994 | *Fusarium semitectum*, *F. pallidoroseum*, *F. monoliforme*, *Curvularia pallenscens*, *C. lunata*, *Drechslera maydis*, *Penicillium* spp., *Rhizopus* spp. | Ekpo and Banjoko (1994) |
| 2004 | *Fusarium graminearum* (14.7%), *F. pallidoroseum* (7.5%), *F. verticilloides* (49.4%), *F. solani* (3.3%), *Rhizopus* spp. (1.3%), *Mucor* spp. (1.5%), *Nigrospora* spp. (2.2%), *Aspergillus flavus* (6.8%), *A. niger* (1.3%), *A. fumigatus* (1.7%), *A. ochraceus* (1%), *Curvularia* spp. (4.5%), *Penicillium chrysogenum* (1.8%), *P. citrinum* (1.2%), *Cladosporium* spp. (3.4%) | Bankole and Mabekoje (2004) |
| 2007 | *Aspergillus* spp. (6.82%), *Mucor* spp. (77.27%), *Rhizopus* spp. (9.09%), Yeast sp. (4.55%) | Okoli et al. (2007) |
| 2014 | *Aspergillus parvisclerotigenus*, *A. flavus* (98.5%), *Aspergillus tamarii* (1.4%) | Perrone et al. (2014) |
| 2019 | *Aspergillus niger* (7.87%), *A. flavus* (5.48%), *A. fumigatus* (4.11%), *A. versicolor* (2.05%), *A. glaucus* (1.17%), *A. terreus* (1.13%), *Penicillium cherasanum* (3.08%), *P. verrucosum*, (2.05%), *P. marneffei* (2.05%), *Fusarium oxysporium* (5.14%), *F. solani* (3.42%), *F. aquaeductuum* (1.13%), *Rhizopus oryzae* (3.42%), *Cunninghamella eleganz* (3.08%), *Verticillium* sp. (4.45%), *Scedosporium prolificans* (0.68%), *Alternaria infectoria* (2.05%), *Fonsecaea pedrosoi* (3.42%), *Malbranchae* sp. (1.17%), *Cladosporium carrionii* (2.74%), *Cryptococcus albidus* (2.40%), *Cryptococcus laurentii* (1.71%), *Candida albicans* (5.82%), *C. stellatoides* (10.62%), *C. stellatoides* (10.62%), *C. glabrata* (5.14%), *C. rugosa* (4.45%), *Saccharomyces cerevisiae* (8.56%) | Oyeka et al. (2019) |
| 2022 | *Fusarium oxysporum* (21.43%), *Aspergillus. niger* (42.86%), *A. flavus* (14.29%), *Penicillium* sp. (7.14%), *Rhizopus stolonifera* (14.29%) | Abdulrazak et al. (2022) |
| 2023 | *Aspergillus clavatus* (8%), *A. flavus* (32%), *A. niger* (32%), *A. fumigatus* (24%), *A. ochraceus* (8%), *Curvularia lunata* (8%), *Penicillium chrysogenum* (12%), *P. citrinum* (8%), *Fusarium graminearum* (24%), *F. pallidoroseum* (8%), *F. verticillioides* (80%), *F. solani* (12%), *Rhizopus* spp. (20%), *Mucor* spp. (20%). | Mabekoje et al. (2023) |

## 2. Major fungi associated with maize contamination in Nigeria and their health implications

### *2.1 Aspergillus*

#### 2.1.1 Description

*Aspergillus* is a large genus of anamorphic fungi with approximately 300 species (Baker and Bennett, 2007) and it was described by Micheli in 1729 (Afzal et al., 2013). The most prevalent species in the genus include *Aspergillus niger*, *Aspergillus flavus*, *Aspergillus fumigatus*, *Aspergillus parasiticus*, *Aspergillus nidulans* (Eidam) G. Winter, *Aspergillus glaucus* (L.) Link, *Aspergillus ustus* (Bainier) Thom & Church, and *Aspergillus terreus* (Bennett, 2010). Conidiogenesis is the primary asexual reproduction method in *Aspergillus* species and this process involves the development of specialized structures called conidiophores, which produce millions of asexual spores known as conidia, facilitating widespread dispersal and colonization (Bennett, 2010). Conidia and conidial head shape are most important morphological characteristics considered by mycologist to identify *Aspergillus* species (Mohamed and Hosny, 2018). The colonies are often blue-green in appearance, and their thick coating of conidiophore felt gives them a suede-like surface. Conidial heads are usually uniseriate and columnar, measuring 50 to 400 µm. This genus can be found in many parts of the world (Smith, 2012). The major mycotoxins produced by *Aspergillus* include ochratoxin A (OTA), aflatoxins (AFs), and less predominant toxins such as patulin. The optimum temperature range for *A. parasiticus*, *A. flavus*, and specific strains of *A. nomius* and *A. tamarii* to produce AFs is between 25 and 30 °C, with a kernel moisture content of approximately 18% (Li et al., 2016). These toxins are found in different food commodities and are commonly regulated with different threshold limits depending on the matrix (Taniwaki et al., 2018).

**Table 5 –** Fungi in the Sudan savanna (SS) with values between brackets representing the % of occurrence of the isolates.

| Year | Fungi | References |
|---|---|---|
| 2019 | *Aspergillus flavus* (30.9%), *A. fumigatus* (20.1%), *A. niger* (16.6%), *Fusarium* spp. (6.2%), *Rhizopus stolonifera* (7.1%), *Mucor hiemalis* (9.7%), *Eurotium herbarium* (4.4%), *Penicillium* spp. (5%) | Keta et al. (2019) |
| 2020 | *Penicillium notatum* (3%), *Fusarium moniliforme* (10%), *F. graminearum* (26%), *F. verticilliodes* (9%), *Aspergillus flavus* (20%), *A. niger* (15%), *A. fumigatus* (2%), *A. parasiticus* (15%) | Shehu et al. (2020) |
| 2021 | *Aspergillus niger* (16%), *A. fumigatus* (14.03%), *A. terreus* (13.28%), *A. flavus* (12.28%), *Mucor racemosus* (13%), *Fusarium* sp (10.52%), *Cephalosporium* sp. (10.52%), *Penicillium* sp. (9.77%) | Mubarak and Keta (2021) |
| 2023 | *Aspergillus flavus* (36%), *A. niger* (6%), *A. fumigatus* (8%), *Penicillium chrysogenum* (4%), *P. citrinum* (8%), *P. pinophilum* (12%), *Fusarium graminearum* (16%), *F. pallidoroseum* (15%), *F. verticillioides* (72%), *F. solani*, *Rhizopus* spp. (28%), *Mucor* spp. (8%) | Mabekoje et al. (2023) |

2.1.2 Health implications

*Aspergillus* species are notorious for producing a variety of mycotoxins that pose significant health risks to humans and animals. These toxins can lead to both acute and chronic health issues, including immunosuppression, carcinogenic effects, and organ damage. According to Perrone and Gallo (2017), the primary mycotoxins generated by *Aspergillus* species are aflatoxins ($B_1$, $B_2$, $G_1$, and $G_2$), ochratoxin A, fumonisins ($B_2$ and $B_4$), patulin, sterigmatocystin, cyclopiazonic acid, penicillic acid, citrinin, cytochalasin E, verruculogen, and fumitremorgin A and B. The most harmful and cancer-causing mycotoxins are aflatoxins, particularly aflatoxins $B_1$ which has been linked to human liver cancer in some regions of the world according to epidemiological data (Hamid et al., 2013). Moreover, animals that consume foods contaminated with aflatoxin may develop chronic aflatoxicosis as a result of aflatoxin toxicity (Perrone and Gallo, 2017). Symptoms of aflatoxicosis include reduced weight gain, haemorrhage, and suppression of the immune system. In this respect, extensive research has been carried out on the natural occurrence, identification, characterization, biosynthesis, and genetic regulation of aflatoxins (Kamei and Watanabe, 2005). Fumitremorgin A and B produced by *Aspergillus fumigatus*, exhibit immunosuppressive effects, which can exacerbate the risk of infections in exposed individual (Li, 2011). Sterigmatocystin, produced by several *Aspergillus* species including *A. versicolor* (Vuill.) Tirab and *A. flavus*, shares structural similarities with aflatoxins and has been implicated in carcinogenic activity (Zingales et al., 2020).

### *2.2 Penicillium*

#### 2.2.1 Description

More than 350 *Penicillium* species have been described (Visagie et al., 2014). Many of these species are recognized as potential sources of mycotoxins and are frequently found as contaminants on a variety of substrates. Their morphological features include quick growth in green or occasionally white hues, with dense felts of conidiophores making up most of the colonies (Perrone and Susca, 2017). Chains of single-celled conidia are formed as a basal array from specialized conidial cells called phialides. Phialides have a brush-like appearance and can be formed singly, in clusters or from branched rimedids of *Penicillium* spp. (Visagie et al., 2016). Many new species have been recorded, such as *P. isariiforme* Stolk & J.A. Mey, *Penicillium johnkrugii*, K.G. Rivera, Houbraken & Seifert, *P. verrucosum*, *P. cyclopium* Westling, *P. griseofulvum*, *P. buchwaldii* Frisvad & Samson, and *P. corvianum* Visagie & Seifert (Frisvad et al., 2013; Perrone and Susca, 2017). *Penicillium chrysogenum*, *P. citrinum*, *P. islandicum* Sopp, and other *Penicillium* species, including *P. italicum* Wehmer and *P. adametzioides* S. Abe, have been found in saline soils, saline environments, saltwater lakes and hypersaline regions (Leitão, 2009). However, certain species prefer acidic or alkaline environments (Yadav et al., 2018). As mentioned earlier, *P. chrysogenum*, *P. citrinum*, *P. oxalicum*, *P. digitatum* (Pers.) Sacc, and *P. flavigenum* Frisvad & Samson have all been discovered in acidic soil; in this instance, the majority of *Penicillium* species thrive at low pH (Diao et al., 2019). Additionally, the *Penicillium* spp. can be found growing in various environments, including the phyllosphere, the rhizosphere, as endophytes, and on a variety of decaying fruits (Park et al., 2020). Reports of *Penicillium* spp. have been made from a variety of plants, including rice, giant dogwood, bananas, wheat and orchid trees (Mwajita et al., 2014). Species of *Penicillium* are frequently encountered in handling, processing and postharvest operations. The production of mycotoxins can be hazardous to human and animal health and is a major cause of food contamination caused by these organisms. Toxins produced by *Penicillium* species include cyclopiazonic acid, citreoviridin, citrinin, brevianamid A, griseofulvin, fumitremorgin B, and ochratoxin A (Waing et al., 2015).

#### 2.2.2 Health impact

*Penicillium* spores are common in the "normal" airborne fungal community. *Penicillium* species are ascomycetes closely related to *Aspergillus* but not capable of the same effects (*Penicillium marneffei* Segretain, Capponi & Sureau is a notable exception). However, the production of secondary metabolites is common in *Penicillium* species. Some can be nephrotoxic, e.g., *P. aurantiogriseum* Dierckx, *P. verrucosum*, and *P.* frei Frisvad & Samson. Allergies to *Penicillium* and other fungi are common in individuals with asthma (Kadaifciler and Demirel, 2017). Foods and feed contaminated with *Penicillium* spp. may include a variety of mycotoxins from the same or distinct species. Citrinin, for example, is a mycotoxin belonging to the citrinin-type class and is produced by *P. citrinum*, *P. expansum* Link, *P. radicicola* Overy & Frisvad and *P. verrucosum* (Pitt, 1988). Citrinin has been shown in numerous animal investigations to have cytotoxic and genotoxic effects in both *in vivo* and *in vitro* systems. These effects include nephrotoxicity, effects on embryos, and intestinal cell apoptosis (Flajs and Peraica, 2009). *Penicillium Carneum* (Frisvad) Frisvad, *P. expansum*, and *P. griseofulvum* produce mostly patulin, a five-membered lactone, as a secondary metabolite (Tannous et al., 2017). Acute manifestations include seizures, agitation, nausea, dyspnoea, pulmonary congestion, oedema, hyperaemia, distension of the gastrointestinal tract, degradation of epithelial cells, intestinal bleeding, inflammation, and ulceration. In mice, chronic exposure can have teratogenic, immunosuppressive, neurotoxic, immunotoxic, genotoxic, and perhaps carcinogenic consequences (Otero et al., 2020). According to the International Agency for Research on Cancer (IARC, 2006), patulin is categorized as an agent for which there is insufficient or limited evidence of carcinogenicity in humans and experimental animals. Ochratoxin A (OTA) is produced primarily by *Penicillium verrucosum* and *Penicillium nordicum* Dragoni & Cantoni ex C. Ramírez (Longobardi et al., 2022). OTA is known to cause nephrotoxicity (kidney damage) and has been linked to kidney cancer in animal studies (Longobardi et al., 2022). The evidence regarding its carcinogenic potential in humans remains inconclusive, although it is considered a potential risk factor for kidney damage and other toxic effects on foetal development and the immune system (Perrone and Susca, 2017).

### *2.3 Fusarium*

#### 2.3.1 Description

Members of the genus *Fusarium* produce a wide array of cottony mycelia that are pink, yellow and purple (Abdel-Azeem et al., 2019). However, this characteristic is not enough to distinguish the members of the *Fusarium* genus. The primary way to categorize *Fusarium* species is the presence of asexual spores, or easily identifiable banana-shaped macroconidia, which are essential to assign a species in the *Fusarium* genus (Abdel-Azeem et al., 2019). Species of *Fusarium* produce three distinct spore types: macroconidial or microconidial asexual reproductive structures and chlamydospores (Ajmal et al., 2023). Most monophialides and polyphialides in aerial mycelia produce septated macroconidia. However, short monophialides in specialized structures, known as sporodochia, can also create septated macroconidia (Santos et al., 2019). Microconidia are formed in the aerial mycelium in clumps or chains on both monophialides and polyphialides. The variability in the shapes and size of microconidia remains the most crucial feature in differentiating the species (Santos et al., 2019). Chlamydospores are resistant structures with high lipid contents and thick walls. The genus *Fusarium* is enormous, with many distinct members that can be isolated as saprobes, endophytes, or pathogens from soil and plants (Summerell et al., 2010). Species such as *Fusarium graminearum*, *Fusarium verticillioides*, *Fusarium equiseti*, *Fusarium semitectum*, *Fusarium solani*, *Fusarium proliferatum*, and *Fusarium nygamai* L.W. Burgess & Trimboli are recognized as pathogens that adversely affect a variety of plants (López-Moral et al., 2024).

*Fusarium* species produce secondary metabolites (such as trichothecenes, fumonisin, and zearalenone), which vary widely in chemical form (Santos et al., 2019). Additional secondary metabolites that may be significant as mycotoxins include fusaric acid, fusarin, moniliformin, beauvericin, culmorin, and enniatins. These species can colonize maize and small-grain cereals such as wheat, sorghum, barley and oats. Depending on the type of crop species involved, the location, and the surrounding environmental factors, the dominant species may change (Pfordt et al., 2020).

#### 2.3.2 Health implications

*Fusarium* spp. produce a plethora of mycotoxins such as fumonisin, which has hepatotoxic, neurotoxic, and carcinogenic effects on human health. Fumonisin exposure has been associated with increased incidences of neural tube abnormalities (Gelineau-van et al., 2009), esophageal cancer (Alaouna et al., 2019), and stunted growth in children (Tessema et al., 2021). Fumonisin can also harm the liver, weaken the immune system, interfere with sphingolipid metabolism, and induce oxidative stress. These effects can result in illnesses such as porcine pulmonary edema (PPE) in pigs and equine leukoencephalomalacia (ELEM) in horses (Chen et al., 2021). Additionally, exposure to fumonisin has been linked to developmental toxicity, renal impairment, and reproductive toxicity (Chen et al., 2021). Fumonisin is classified by the International Agency for Research on Cancer (IARC) as "possibly carcinogenic to humans" (Group 2B) (Claeys et al., 2020). According to Zentai et al. (2019), the main way that humans are exposed to fumonisin is through contaminated maize and maize-derived products.

## 3. Discussion

The results presented in the previous section reveal the critical state of contamination of maize by mycotoxigenic moulds and some pathogenic yeasts in the different agroecological zones of Nigeria. In total, 34 publications were identified and reviewed. The articles have data from only five agroecological zones. No data are available on the prevalence of fungi contaminating maize in MA and SHS. The information from the available studies revealed that of the 39 different fungal genera isolated 36 were moulds and 3 yeasts. In total, 87 species of fungi were identified from the 5 agroecological zones. The genera of fungi contaminating maize included: *Aspergillus*, *Fusarium*, *Penicillium*, *Mucor*, *Rhizopus*, Thermomyces, *Mucor*, *Rhizomucor*, *Absidia*, *Botryodiplodia*, Sycephalus, *Paecilomyces*, *Helminthosporiurn*, *Chaetomium*, *Cladosporium*, *Thermoascus*, *Acremonium*, *Syncephalastrum*, *Alternaria*, *Drechsiera*, *Cephalosporium*, *Collectrocrichum*, *Curvularia*, *Nigrospora*, *Trichoderma*, *Macrosporum*, *Botrytis*, *Scopulariopsis*, *Eurotium*, *Cunninghamella*, *Verticillium*, *Scedosporium*, *Fonsecaea*, *Malbranchae*, *Cladosporium*, *Ceplosporium*, *Talaromyces* sp. The isolated yeast genera were *Cryptococcus*, *Candida*, and *Saccharomyces*. The most common types of mould were *Aspergillus* spp. with a frequence of 37.31%, *Fusarium* spp. with a frequence of 23.13%, *Penicillium* spp. with a frequence of 13.76%, *Rhizopus* spp. with a frequence of 5.43%, *Mucor* spp. with a frequence of 4.71%, *Botryodiplodia* spp. with a frequence of 1.44%, *Cladosporium* spp. with a frequence of 1.44% and *Curvularia* spp. with a frequence of 1.08%.

When we look at the data chronologically, we notice that the works carried out in the 1960s and 1970s by Okafor (1966, 1968), Broadbent (1967, 1969), and Oyerinan (1973a,b) present certain genera, such as *Rhizomucor*, *Absidia*, *Paecilomyces* and *Syncephalastrum*, which have disappeared over time. On the other hand, the species *Botryodiplodia theobromae* identified by Broadbent (1967, 1969) and Oyerinan (1973a,b) in the DS agroecological zone reappeared in recent research carried out by Adetayo et al. (2022) in the same agroecological zone. Onyenka et al. (2005) reported that this fungus is present in more than 70% of farms surveyed in Nigeria and is linked to large yield losses in approximately 80% of crop harvests. This disappearance could be explained by changes in climate. Temperature plays a critical role in the growth and development of fungi, including *Rhizomucor* spp., *Abidia* spp., *Paecilomyces* spp., and *Syncephalastrum* spp. (Van Rhijn and Bromley, 2021). Each of these genera has specific temperature preferences that significantly influence their growth rates and overall viability in maize. *Rhizomucor* species are known to thrive at relatively high temperatures, with optimal growth typically occurring at approximately 30 – 35 °C (Van Rhijn and Bromley, 2021). Some strains can tolerate temperatures up to 54 °C, which allows them to compete effectively in warmer environments. However, temperatures exceeding their tolerance can lead to reduced growth or death of *Absidia corymbifera*, a representative of this genus, which prefers mesophilic conditions and generally grows best between 25 °C and 30 °C. While it can tolerate slightly higher temperatures, prolonged exposure to temperatures above 37 °C can inhibit its growth. Species such as *Paecilomyces sinclairii* show optimal growth at approximately 30 °C, with increased metabolic activity and faster growth rates observed within this temperature range. Higher temperatures generally increase its growth, although extreme heat can lead to stress and reduced viability (Williams et al., 2024).

The results presented in the last decade include new species such as *Scopulariopsis brevicaulis* (Sacc.) Bainier, which was isolated by Akande et al. (2017), *Eurotium herbarium* (Wiggers) Link, which was identified by Keta et al. (2019) *Cunninghamella eleganz*, *Verticillium* sp., *Scedosporium prolificans*, *Fonsecaea pedrosoi*, *Malbranchae* sp., *Cladosporium carrionii*, which were identified by Oyeka et al. (2019) and *Talaromyces sayulitensis*, which was identified by Ekpakpale et al. (2021). Given that these species are responsible for major disease outbreaks in humans and animals, preventive measures are urgently needed to prevent their re-emergence in maize production and even other foods in Nigeria.

Mould contamination in maize was more prevalent in farm samples (39.49%) than in market (33.12%) and stored (27.49%) samples. This variation can be attributed to factors that affect fungal growth and contamination. The contamination process begins in the field, where high humidity, temperature, and moisture levels are conducive to fungal development. Farmers often harvest maize under conditions that may not be ideal, making the crop more vulnerable to mould infestation. Traditional drying practices, such as drying maize directly on the ground, have been identified as major contributors to fungal contamination during both the pre- and postharvest periods (Bilal et al., 2023). Inadequate postharvest management further exacerbates this issue, as many farmers store maize in humid and poorly ventilated spaces, increasing the moisture content and promoting mould growth. On the other hand, market samples tend to benefit from better postharvest handling, including improved drying and storage methods that lower moisture levels and inhibit fungal growth (Ekwomadu et al., 2018).

Different mould species are typically found at various stages of maize handling. For example, *A. flavus* is commonly found in both field and storage samples but it is more abundant in farm samples because of inadequate handling practices (Agbetiameh et al., 2018). Other species, such as *Fusarium acuminatum*, *Penicillium thomii* S. Abe, *P. otrametous*, *P. wortmannii*, *P. dupontii*, *P. luteum*, *Chaetomium globosum* Kunze, *Chaetomium virginicum* L.M. Ames, *Syncephalastrum racemosum*, and *Thermoascus aurantiacus* Miehe, have been specifically associated with farm samples. These fungi introduce a complex mix of potential benefits and risks to maize farming. While *C. globosum* has shown potential as a biocontrol agent against certain pathogens and can even promote plant growth, its toxicity requires careful management (Elshahawy et al., 2022). Additionally, the roles of *Chaetomium virginicum*, *Syncephalastrum racemosum*, and *Thermoascus aurantiacus* present intriguing opportunities for further research into how fungal biology can be harnessed for more sustainable agricultural practices that increase crop health and productivity.

## Conclusion

The objective of this work is to present the historical fungal profile of fungi contaminating maize grown in the different agroecological zones of Nigeria. Among the 7 agroecological zones in Nigeria, only 5 have historical data on the fungal profile of maize. No studies have been identified in the MA and SHS agroecological zones. From these studies, 39 different fungal genera were isolated, including

36 mould fungi and 3 yeasts. Eighty-seven species of mould were identified. The most common fungal species detected were from *Aspergillus*, *Fusarium*, and *Penicillium* genera. Fungal contamination was greater in the farm samples (39.49%) than in the market (33.12%) and stored (27.49%) samples. Moreover, new fungal species have been identified over the last decade, and the resurgence of certain fungal species has disappeared over time. Nigeria should therefore take necessary preventive measures to control fungal contamination of the staple to improve public health and the national and international trade of maize.

**Acknowledgements**
This work was supported by the Tertiary Education Trust Fund, National Research Fund (TETFUND NRF), Federal Republic of Nigeria, Grant No: TETF/ES/DR&D-CE/NRF2021/SETI/AFS/00335/01VOL.1

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