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Postharvest handling practices and mycotoxin occurrence along the dried *berbere* chilli pepper value chain: A case study from Northern Ethiopia

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ABSTRACT

Berbere, the hot pepper spice, is a central ingredient in Ethiopian cuisine. This study aimed to deepen understanding of the agricultural and postharvest handling practices and incidence of aflatoxins and ochratoxins at different stages of the domestic *berbere* (*Capsicum frutescens)* value chain in the Amhara region of Northern Ethiopia. The main actors in the *berbere* value chain in Ethiopia are farmers, assemblers, wholesalers, retailers, industrial processors, and domestic consumers. A series of semi-structured questionnaires were developed and used to interview 90 stakeholders from across these different value chain stages to learn about their *berbere*-related activities and challenges. Additionally, a random sampling method was used to collect 100 *berbere* samples (80 samples of whole dry *berbere* pods and 20 samples of *berbere* powder) from across the different focal value chain stages (harvesting, storage, processing, and retail) for analysis to determine whether aflatoxin and ochratoxin were present above the maximum recommended thresholds. In the Amhara region, most farmers typically cultivate *berbere* on areas of 0.5–1 ha of farmland. The *berbere* harvest is done manually, and the chilli pods are then spread directly on the ground to sun dry. Such drying practices increase the risk of contamination of the produce by dust, debris, and soil-borne fungi. Assemblers purchase *berbere* from the farmers, the pods are then sorted by variety and packed in woven polypropylene bags which are then heaped in store rooms. All the *berbere* samples, from each stage of the value chain analysed were found to test positive for mycotoxins, exhibiting levels of >20 ppb and >2 ppb of total aflatoxin and ochratoxin, respectively. The promotion of a range of integrated pest and postharvest management actions with the different value chain actors are recommended to improve the quality and safety of *berbere* within these important domestic value chains.

1. Introduction

Chilli pepper (*Capsicum frutescens*) is a widely cultivated crop belonging to the Solanaceae family and is believed to have originated from South America (Chakrabarty et al., 2017; Boseland and Votava, 2000). It was introduced to Asia and Africa in 1493, and globally it has become an important crop with around 4,255,050 tonnes of dried chilli produced in 2019 (FAOSTAT, 2021). India is the leading producer of dry hot red pepper, while Ethiopia is ranked as the fourth-highest-producing country in the world, with an annual production of 313,115 tons in 2019 (FAOSTAT, 2021). However, despite Ethiopia being a leading producer of chilli pepper, the country ranks low with regards to chilli pepper exports due to issues related to product quality and food safety (Boseland and Votava, 2000). In general, most (96%) of the spices produced in Ethiopia are currently consumed domestically, and chilli pepper accounts for over 80% of Ethiopia's total spice production (Sendrowicz and Dubelaar, 2020). Over 1.1 million farming households in Ethiopia are estimated to be engaged in the farming of spices (Sendrowicz and Dubelaar, 2020).

In Ethiopia, hot pepper is known as *berbere* (here after the term *berbere* is used when referring to Ethiopian dry red hot chilli pepper). Within Ethiopia, *berbere* is commonly cultivated in locations with altitudes ranging from 1400 to 1900 m above the sea level, and a mean annual rainfall and temperature range of 600–1200 mm, 25–28 °C, respectively. The production of *berbere* by smallholder farmers is concentrated in Amhara, Oromia, and Southern Nations, Nationalities

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and Peoples' (SNNP) Region states of Ethiopia (Abebayehu et al., 2014). The *berbere* crop is typically rotated with maize, which is grown as a primary staple food crop for home consumption. *Berbere* is usually planted in April/May when the rainy season starts and harvested from October to February (dry season) (Boseland and Votava, 2000; Gobie, 2019). In Ethiopia, *berbere* cultivation is practised at small-scale levels using traditional practices. The harvest and postharvest operations include traditional harvesting, drying, sorting, storage, and milling practices.

In many Ethiopian dishes, highly pungent dried *berbere* powder is an important ingredient. The fine-powdered pungent product known as "*berbere* powder/*mitmita* (extra hot version of the powder)", imparts both flavour and colour to the traditional Ethiopian sauce "*Stew or Wot*". The average daily consumption of *berbere* by Ethiopian adults is estimated at 15 g, which is higher than tomatoes and most other vegetables (Gobie, 2019).

The different *berbere* varieties have a range of pod colours from pale to deep red. Usually, *berbere* pods are transformed into *berbere* powder and oleoresins. Both are used to impart colour and flavour to different foods. Capsaicin, the pungent alkaloid is the major bioactive compound in *berbere* (Lu et al., 2020). The capsaicin concentration in *berbere* reportedly ranges from 0.1 to 3.2g/100g dry weight (Arimboor et al., 2015). The capsaicin in red *berbere* is reported to have health benefits such as cardio-protective influence, anti-lithogenic effect, anti-inflammatory and analgesia, thermogenic influence, and beneficial effects on the gastrointestinal system (Srinivasan, 2016). Chopan & Littenberg, (2017) reported that consumption of hot *berbere* was associated with reduced mortality and concluded that, *berbere* is beneficial for the human diet. Other work suggests that *berbere* can be used to alleviate human dietary micronutrient deficiencies (Olatunji and Afolayan, 2018).

The presence of fungal toxins in *berbere* is viewed as one of the major quality and safety challenges as they are known to be responsible for a wide range of health problems. Fungal or mycotoxins are naturally occurring toxic low molecular weight metabolites produced by certain fungal species and can be found in food. Warm and humid environments are known to encourage the growth of mycotoxin-producing fungi and certain food crops such as cereals, nuts, spices, dried fruits, and coffee beans are particularly affected by the growth of these fungi in humid environments (Fufa & Urga,1996; Patriarca and Pinto, 2017). Consumption of mycotoxin-containing products can cause various health-related impacts ranging from acute poisoning to longer-term chronic effects on immunity, growth and different cancers (Fufa & Urga,1996; Liew and Mohd-Redzwan, 2018). Links between gall bladder cancer and the consumption of aflatoxin-contaminated *berbere* were reported by Tsuchiya et al. (2011).

To our knowledge, despite the importance of *berbere* in Ethiopian domestic food systems, limited documented information on the post-harvest handling and incidence of aflatoxins and ochratoxins exists for *berbere* in Northern Ethiopia. This study aims to address this knowledge gap in order to help inform the development and testing of practical strategies for reducing quantity and quality losses of *berbere* at and after harvest and to support and strengthen the livelihoods of the different actors involved in the *berbere* value chain.

2. Materials and methods

2.1. Study area

The study location was Bure district (*woreda*) of Amhara National Regional State of Ethiopia. Bure is located 400 km Northwest of Addis Ababa and 148 km southwest of Bahir Dar city. Bure *woreda* receives a relatively high rainfall amount with a balanced distribution pattern. The mean annual rainfall is reported to range from 1386 to 1757 mm. The altitude ranges from 713 to 2604 m above sea level. Long-term annual mean temperature ranges from 14 °C to 24 °C. Maize, wheat, teff, finger millet and barley are the main cereals produced in the region. *Berbere* is mainly produced under rain-fed conditions in the low and mid-altitude areas of Bure *woreda* (ILRI 2007). Farmers in the lowland area grow *berbere* on an average of 0.5–1 ha of land annually. Given this large area of land planted to *berbere*, farmers use a direct sowing method (Shimelis, 2021).

2.1.1. Selection of study location

Bure district, West Gojjam zone, Amhara region was purposively selected as the study location due to it being within the main *berbere* production areas. In Bure district, red pepper is a major cash crop that is mainly produced by smallholder farmers.

2.2. Selection of survey participants

2.2.1. Berbere farmers

Three kebeles, Alefa, Dedun, and Wadero, within Bure district were purposively selected as the majority of farmers engaged in *berbere* cultivation live within them. These three kebeles cumulatively contain 12 sub- kebeles (a sub-unit of a kebeles, these are locally recognized units although not official units). Five sub- *kebeles* (5th, 8th, 9th, 10th, and 11th) were randomly selected. From each selected sub- *kebeles*, every sixth house was selected for interview. In sub- *kebeles* 5, 8, and 9, interview data was collected from six *berbere* farming households as the population is similar (i.e., each have 38 to 40 households which cultivate *berbere*). In sub- *kebele* 10, interview data was collected from 7 households as it contains a total of 46 households which cultivate *berbere*. In sub- *kebele* 11, data was collected from 5 households as the population there is smaller, with a total of 34 households which cultivate *berbere*.

2.2.2. Berbere assemblers

The snowball sampling method was used to select assemblers. Assemblers were initially identified in the market area. Contact information of other assemblers was then collected from the identified assemblers. Interview data was collected from a total of 10 assemblers randomly selected from the collected contacts.

2.2.3. Berbere wholesalers

Around 32 wholesalers are based in the Bahir Dar City market area (kebele 4). A systematic sampling approach was used to select the wholesaler sample. Every third wholesaler on the list of wholesalers was selected and a total of 10 were interviewed.

2.2.4. Industrial berbere processors

The snowball sampling method was used to select industrial processors. Initially, one industrial processor was identified through contacts, and that person then connected the team to other processors and so on. Data was collected from 10 industrial processors located in Bahir Dar City.

2.2.5. Domestic berbere processors

Random purposive sampling was used to identify 10 domestic processors within Bahir Dar City, where households prepare *berbere* powder, a total of 10 domestic processors were interviewed.

Information was collected on socio-demographical aspects; *berbere* farming practices, harvesting, post-harvest handling and preservation and processing. The survey was done between 29th May to 1st July 2020.

2.3. Dried berbere pod/powder sample collection

During the survey, a total of 100 samples were collected from across the different stages of the value chain. Of the 70 samples of red *berbere* pods, 30 came from the farmers, 10 from the assemblers, 10 from the wholesalers, 10 from the retailers and 10 from the industrial processors. Of the 30 samples of red *berbere* powders, 10 came from industrial processors, 10 from domestic processors and 10 from the market. *Berbere* pods from the farmers were collected from the different places within their storage facilities to form a representative sample per farmer (each composite sample was a combination of three samples). In the case of *berbere* stored in bags, pods were collected from different bags to form the sample. In the case of *berbere* powder, sub-samples were selected from different areas of the bag/container and different bags if more than one bag existed. Immediately following collection, all the samples were placed into three layers of polythene bags and sealed to prevent air entry and then stored in the refrigerator at 4 °C until further analysis was done (within two months). The samples were stored under refrigerated conditions to avoid further growth of any fungi which were present.

2.4. Determination of aflatoxin and ochratoxin presence

The ELISA kit method was used to determine the presence of aflatoxin and ochratoxin in each sample, and whether they exceeded the maximum tolerable levels. Each *berbere* pod sample was ground for 10 min into a coarse powder using the laboratory mortar and pestle (Porcelain Mortar & Pestle, India). After each sample was ground, the mortar and pestle were cleaned with ethanol twice before processing the next sample. The *berbere* powder samples collected from stakeholders were used directly without any further grinding. The powders were used for the determination of both toxins following the extraction process described in 2.4.2 and 2.4.5 which is as per the instructions given by the ELISA kit manufacturer without any modifications.

2.4.1. Aflatoxin determination

VICAM-AflaCheck® (VICAM, USA) (Manufacture catalogue numbers 100000173, 175, 812, 813 and 827) was used for the qualitative determination of the aflatoxins in *berbere* samples. AflaCheck® Test Strips are provided for fast accurate determination of the aflatoxins at 10 ppb and 20 ppb levels only. The two steps described in 2.4.2 and 2.4.3 were followed to determine aflatoxin presence in the samples using the kit.

2.4.2. Extraction of the sample for aflatoxin determination

The extraction procedure was carried out following the instructions provided by the ELISA kit supplier. Five grams of the ground sample was added to the extraction tube provided by the manufacturer, and a new tube was used for each sample. Exactly 10 ml of 70% Methanol was added into the extraction tube. The tubes with the contents were mixed well for 1 min using a vortex at high speed. The samples were then allowed to settle for 3 min as per the ELISA kit instructions. The supernatant was used for the determination of aflatoxin.

2.4.3. Sample test for aflatoxin

Exactly 250 μL of the supernatant solution (sample extract) was taken into the fresh dilution tube (Eppendorf Tube) using a test pipette (provided by the manufacturer) and 250 μL of distilled water was added using a fresh test pipette. After closing the cap of the tube, the solution was mixed using manual shaking. The test strip (ELISA strip) was then inserted into the Eppendorf tube and left to stand for 5 min after which the results were read. Depending on the development of the coloured lines on the strip the test was determined as positive or negative. For each sample, the strip was also checked for the development of the control line. If the control line does not develop the test is considered invalid and another new strip would then be used to check the same sample. The sample extraction and determination are presented in the Supplementary Information Fig. 1.

2.4.4. Ochratoxin determination

For determination of the Ochratoxin, the Ochra-V Aqua® cassette from VICAM, USA was used. For this test the detection limit is 2 ppb. The catalogue numbers are 176004087 and 10000345.

2.4.5. Extraction of the sample for ochratoxin determination

As per the ELISA kit instructions, 5 ± 0.1g of the ground sample was placed in the extraction tube provided by the manufacturer, a new tube was used for each sample. Then 25 ml of Aqua premix solution which was supplied as part of the kit was added and gently mixed by vortex at minimum speed for 2 min. The sample was filtered into a clean extraction tube supplied in the kit using a fresh piece of fine filter paper for each sample.

2.4.6. Sample test for ochratoxin

Clear filtrate of 100 μL sample extract was added to the Ochra-V strip cassette by dropping 1 drop/second vertically into the sample well. The test cassette was allowed to develop for 5 min on a flat surface. If no development of the control line occurred, the test was considered invalid, and another new cassette was used for the determination of ochratoxin in the same sample. The sample extraction and determination procedures are depicted in Supplementary Fig. 2.

2.5. Determination of water activity (a_W) in the samples

A Lab Master-water activity instrument (Novasina AG, CH-8853 Lachen) was used to determine the water activity of the *berbere* samples. The ground samples were placed in a plastic sample cup, completely covering the bottom of the cup. The sample cup was then placed in the sample chamber and the door of the chamber was closed carefully. Water activity was reported directly from the display panel.

2.6. Data analysis

The survey data was analysed using the statistics package for social science (SPSS) IBM Ver. 18. The main analyses performed were descriptive statistics such as the frequency, percentages, and ranges.

3. Results

The structure of the *berbere* value chain in the Amhara region of Ethiopia is shown in Fig. 1. The surveyed farmers and assemblers in the *berbere* value chain were in Bure district. While the other major value chain actors, the wholesalers, retailers, industrial processors, and home processors were based in Bahir Dar city.

3.1. Berbere agricultural and handling practices at the farmer's level

3.1.1. Socio-demographic characteristics of farmer respondents

The 30 farmer respondents belonged to three *kebeles* (wards or villages), namely Aleafa, Debun and Wadero within the Western Gojam zone. The respondents were distributed across five *woredas* (districts) 5, 8, 9, 10, and 11. Aleafa has previously been reported to be one of the highest *berbere*-producing *kebeles* in Bure (Tesheshigo et al., 2019) (Table 1).

The mean age of respondents was 40 years, and the range was from 19 to 70 years. Of the 30 farmer respondents, 40% were female. Respondents' education status varied from basic education (73% of respondents) to 11th grade (3% of respondents) (Table 1).

3.1.2. Berbere cultivation practices

Among the respondents, the mean area of *berbere* cultivated was 0.65 ha and ranged from a minimum of 0.25 ha to a maximum of 2 ha. Of the respondents, two-thirds were cultivating *berbere* on ≥ 0.5 to ≤ 1 ha of land. In the current study, 80% of respondents practised rain-fed *berbere* production only, with the remaining respondents practising both rain-fed and irrigated production. Almost all the respondents cultivated *berbere* both for sale and for domestic consumption purposes.

The majority (80%) of the respondents were cultivating the Danbure variety of *berbere,* the rest were cultivating the Mareko Fana variety, and only one respondent reported cultivating both varieties. Most of the

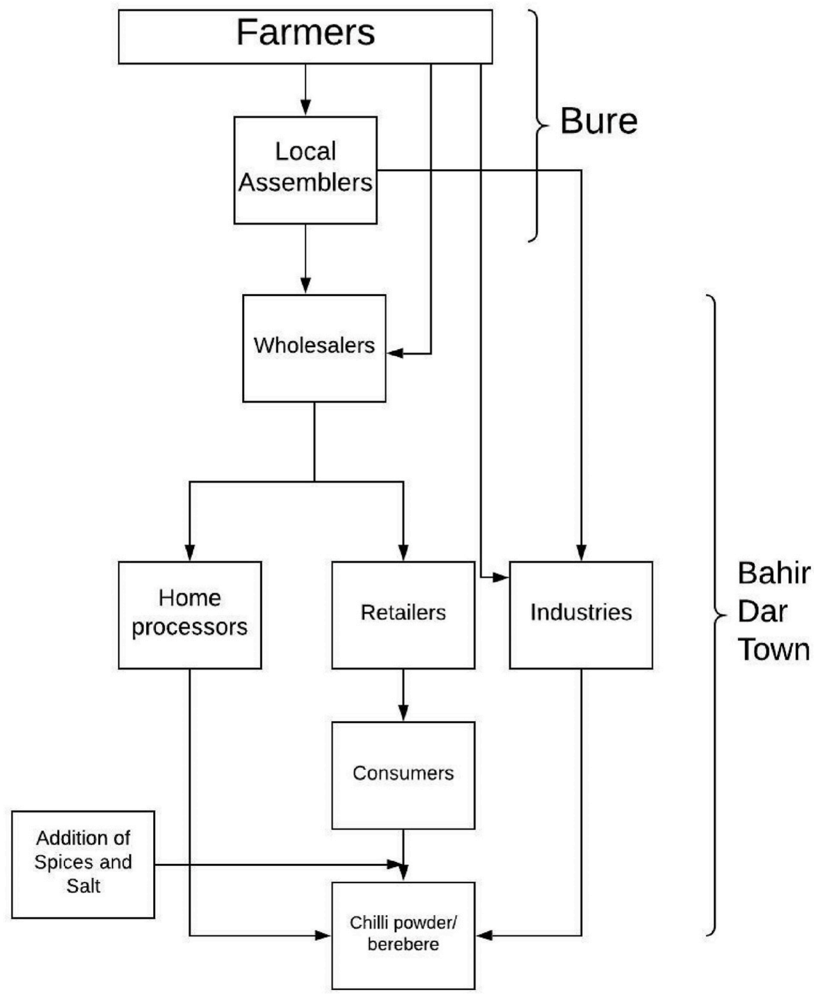

Fig. 1. The value chain for *berbere* red-hot pepper in Bure district and Bahir Dar city, Ethiopia.

Table 1
Socio-demographic characteristics of respondents in Bure district, Amhara region, Ethiopia.

Parameter	Number of respondents	Percentage (%)
Respondent's Kebele		
Alefa	10	33.33
Debun	10	33.33
Wadero	10	33.33
Woreda number	6	20
Woreda-5	6	20
Woreda-8	6	20
Woreda-9	7	23.3
Woreda-10	5	16.6
Woreda-11		
Age		
<20 Years	1	3.33
20–30 Years	8	26.66
31–40 Years	8	26.66
41–50 Years	5	16.66
51–60 Years	5	16.66
>61 Years	3	10.0
Level of education		
No education	0	
Basic education	22	73.33
5–10 grade	7	23.33
>10 grade	1	3.33

respondents (93.3%) plant their *berbere* in June, and the others in July. Harvesting of *berbere* occurred 5–6 months later in November and December (Tables 2 and 6).

Just over half of the farmer respondents (53%) reported facing problems of pests and diseases during *berbere* cultivation (Table 2). These farmers perceived these problems to all be fungal diseases, but none of them knew of or had any control measures to counteract these problems. Weeds in their *berbere* fields were another problem reported by 50% of the farmer respondents. The weed species mentioned translate to grasses mainly, as well as *Guizotia scabra* and *Rumex nervosus*. Around 70% of the respondents practice crop rotation. Prior to cultivating *berbere*, the farmers reported having grown cereals on the land. However, the remaining 30% of respondents grow *berbere* continuously on the same piece of land.

The majority (90%) of respondents reported rainfall occurring during the time of *berbere* flowering (Table 3). Around 90% of respondents reported that rainfall also occurred when *berbere* pods were ready for harvest and during harvesting. Around 70% of respondents reported rainfall occurring during the drying process. All respondents reported rainfall in at least one of the following three important stages of *berbere* growing and handling (flowering, ready for harvesting, drying).

3.1.3. *Drying of the berbere pods*

Regarding the drying of the matured pods after harvesting, around 13% of the farmers practice drying in the field, while 60% dry the pods at their homesteads, and 27% of the respondents use both the field and home for drying (Table 4). Virtually all the farmers surveyed (97%) sun-

Table 2
Agricultural characteristics of *berbere* farmers in Bure district, Amhara region, Ethiopia.

Parameter	Number of respondents	Percentage (%)
Land size under *berbere* cultivation		
0.25–0.5	3	10
0.6–1.00	20	66.6
1.00–1.5	8	26.6
1.6–2.0	1	3.33
>2.00	1	3.33
***Berbere* variety cultivated**		
Danbure	24	80
Mareko	6	20
In which month is *berbere* planting done?		
June	28	93.3
July	2	6.66
In which month is *berbere* harvesting done?		
November	15	50
December	15	50
Is your *berbere* cultivation rain-fed or irrigated?		
Rain-fed	24	**80.0**
Irrigated	0	
Both	5	**20.0**
Does your *berbere* crop suffer any insect/pest/disease damage in the field during production?		
Yes	16	53.3
No	13	43.33
Not sure	1	3.33
Do you use any pest control measures?		
Yes	0	
No	28	93.3
Not sure	2	6.66
Do you typically have weeds growing in the field during *berbere* production?		
Yes	15	50.0
No	14	46.6
Not sure	1	3.33
If yes, name the type of weed		
Rumexnervosus	8	26.66
Guizotiascabra	11	36.6
Grass	8	26.66
Do you use any weed control measures?		
Yes	1	3.33
No	29	96.6
Not sure	0	
Do you use any chemicals to control weed?		
Yes	0	
No	30	100
What type of crop was cultivated in the same field before you planted this red *berbere* crop		
Same crop	9	30
Cereals	21	70
Others	0	

Table 3
Farmers' perceptions of rainfall occurrence during the in-field and postharvest *berbere* stages in Bure district, Amhara region, Ethiopia.

Parameter	Number of respondents	Percentage (%)
Was there rainfall during the flowering time of this *berbere* crop?		
Yes	27	90
No	2	6.66
Do not remember	1	3.33
Did any rainfall occur when this *berbere* crop was ready for harvesting?		
Yes	27	90
No	2	6.66
Do not remember	1	3.33
Did any rainfall occur when you were harvesting this berbere **crop?**		
Yes	26	86.6
No	4	13.33
Do not remember		
Did any rainfall occur when you were drying this *berbere* crop?		
Yes	22	73.33
No	8	26.6
Do not remember	0	

Table 4
Farmers' *berbere* harvest and drying practices in Bure district, Amhara region, Ethiopia.

Parameter	Number of respondents	Percentage (%)
How do you usually tell when your *berbere* is ready for harvesting?		
Calendar (month) calculation	7	23.33
When pods dry up	24	80.0
Other specify (colour)	1	3.33
Do you dry the freshly harvested *berbere* in the field, at home, or somewhere else?		
Field	4	13.3
Home	18	60.0
Both	8	26.6
Others		
Where do you dry the hot pepper/*berbere?*		
Berbere pods are spread directly on the ground	29	96.6
Berbere pods are spread on a plastic sheet or covered on the ground	0	
Berbere pods are spread on a concrete drying area	1	
Others (specify):	0	
How do you dry the hot pepper/*berbere*?		
Sun drying	30	100
Solar drying (Developed Driers)	0	
Artificial dryers/hot-air Mechanical dryers	0	
Others	0	
How long did the *berbere* take to dry to be ready for storage?		
One Week	3	10
Two Weeks	6	20
Three Weeks	1	3.33
Four weeks	20	66.66
How do you tell that the *berbere* pods are dry enough?		
Just by looking at them	2	6.66
By touching them	28	93.33
Using Moisture testers	0	
By indigenous knowledge/(specify what)	0	
Any other methods used	0	
Do you see any fungal infection on the hot pepper pods in the field, before harvest?		
Yes	16	53.5
No	14	46.6
Are you aware that proper drying could control mould/fungal development and maintain the quality of your *berbere*?		
Yes	10	33.33
No	20	66.66
Do you do any sorting/cleaning BEFORE drying the *berbere*?		
Yes	11	36.66
No	19	63.33
Do you do any sorting and grading AFTER drying the *berbere*?		
Yes	21	70
No	9	30

dry their *berbere* by spreading it directly on the ground (Fig. 2A). Only one farmer used a concrete floor for the drying, and none of the farmers use plastic sheets for drying their *berbere* on. The farmers typically sun-dry the *berbere* for a duration of between one week and 30 days, with the majority (70%) stating they dry for four weeks with the duration being dependent on the environmental conditions and the initial moisture content of the pods.

To determine whether the *berbere* is sufficiently dry, manual touching is used by 93% of the respondents, while the other farmers use visual observations (Table 4). Of the farmers, 53% reported that they observe fungal infection/disease on the pods before harvesting. Only 33% of the farmers were aware of the importance of proper drying for maintaining the quality of the *berbere* and avoiding fungal growth during storage (Table 4).

The majority of farmers reported using pod dryness as an indicator of maturity and harvesting readiness (Table 4). While 23% of respondents reported that they considered and followed a calendar-based calculation of the number of days since planting to determine maturity and harvesting.

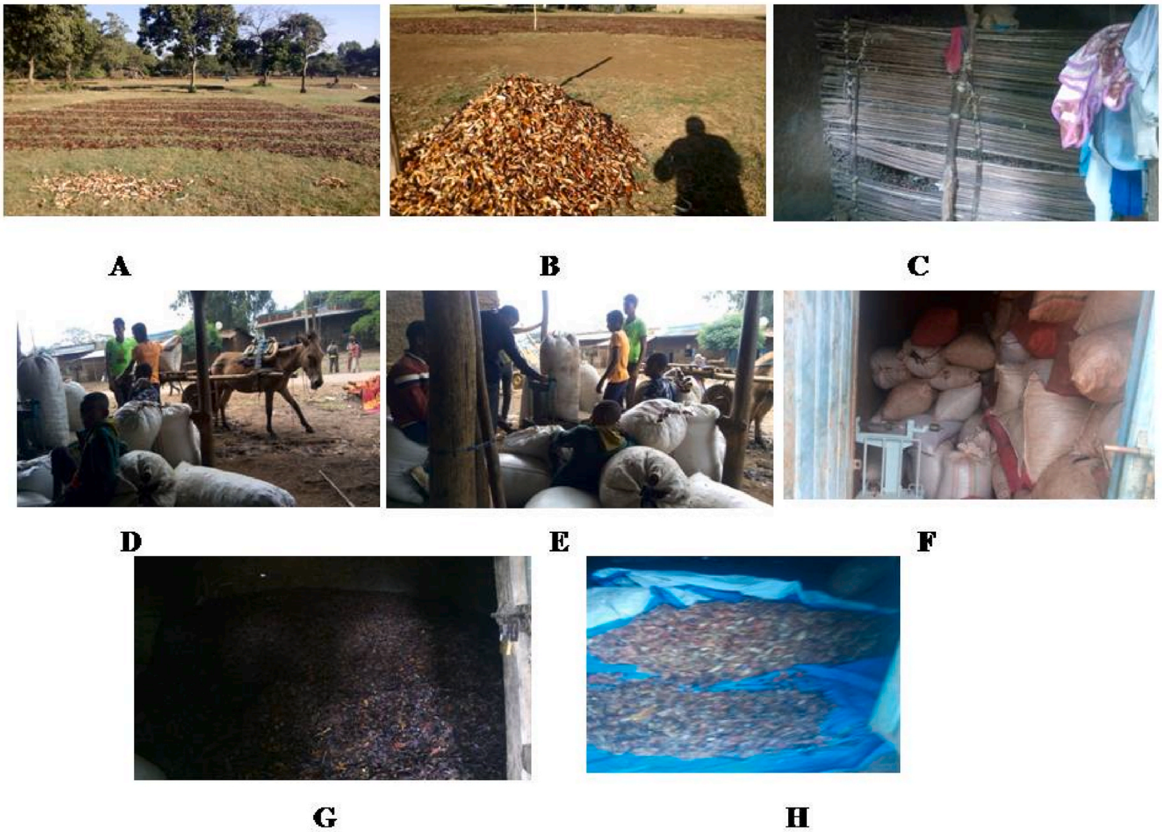

Fig. 2. *Berbere* handling practices at the farmer and assembler stages in Bure district, Ethiopia (A) *Berbere* pods spread on the field for sun drying. (B) Sorted-out colour-less *berbere* at a farmer's homestead. (C) *Berbere* is stored in the traditional storage structure in a farmer's home. (D) Farmers take the *berbere* to an assembler's aggregation point by horse cart. (E) *Berbere* weighing at the assembler's level. (F) Storage of *berbere* in woven polypropylene sacks at the assembler's level. (G) Bulk storage of *berbere* pods heaped in a room at the assembler's level. (H) Sorted *berbere* pods on plastic sheeting at the assembler's level.

3.1.4. Sorting and grading of berbere pods

Sorting of the *berbere* before drying was practised by just 37% of the farmers (Table 4 and Fig. 2B). The farmers who sort their pods before drying, separate the spoiled, broken, fungus-attacked pods and plant debris from the good quality pods. However, following the drying process, 70% of the farmers sort their pods. During this post-drying sorting process, the spoiled, broken, pale or white-coloured *berbere* pods are sorted out, and plant waste and dust are removed. The farmers sort the pods to achieve uniform quality of their *berbere* during storage. Two farmers explained that the poor quality *berbere* they have sorted out would be used for their domestic/home consumption while the good quality *berbere* would be for sale.

3.1.5. Farmer-level storage of berbere

Around 63% of the farmers store their dried *berbere* in a *gotera*, a traditional storage structure constructed from locally available wooden sticks (Table 5 and Fig. 2C). About 13% of the farmers store their *berbere* on the ground in a heap, 13% store it in polypropylene bags and 10% of the farmers use jute bags. The polypropylene bags have a capacity of 20–30 kg; while the jute bags are typical of 50 kg capacity, the *goteras* range in size with capacities from 150 to 2000 kg. Those farmers who heap the *berbere* on the floor reported doing so for 300–1000 kg of the dried crop. On average the farmers reported storing 270 kg of dried *berbere* annually, however, this ranged widely among respondents from a minimum of 100 kg–1000 kg.

Around 57% of the farmers store their *berbere* at their homes, while 27% use co-operatives or society warehouses for storage. Some respondents (17%) store their *berbere* in the field. The mean storage duration of dried *berbere* by farmers was 3.9 months (Table 5). But storage durations ranged between farmers, with 10% of the farmers storing their *berbere* for six months, 33% for five months, 20% for four months, 17% for three months, 17% for two months and 3% for one month. The majority (67%) of the respondents reported that they had not found any signs of fungal growth on their stored *berbere*, while 27% had, and 7% were not sure. In the current study, none of the responding farmers knew about or was aware of mycotoxins. None of the farmers reported pest or disease issues which caused losses after harvest or during storage of their *berbere* (Table 5). None of them use any storage protectants or other practices on their stored *berbere* to maintain its quality.

3.1.6. Postharvest information pathways for berbere

When farmers were asked who had taught them to dry and store their *berbere*, elders were the most commonly cited source (67% of respondents), followed by friends (53%), agricultural officers (7%), and own observations (3%) with many having learnt from both their elders and friends.

3.1.7. Farmers' further knowledge demands for berbere

The main topics the farmer respondents wanted to know more about regarding their *berbere* activities were the causes of the deterioration, methods for extending the shelf life/storage duration while retaining the quality and weed management.

3.2. Berbere handling practices at the assembler level

The ten assemblers interviewed were residents of Bure city which has good road access to the other parts of the country. Farmers from a range of different villages bring their *berbere* to the assemblers located in Bure (Fig. 2D&E). In the study area, all the assemblers are males, and those

Table 5
Farmers' *berbere* storage practices and mycotoxin awareness in Bure district, Amhara region, Ethiopia.

Parameter	Number of respondents	Percentage (%)
What type of packaging/storage systems do you use to store dry *berbere*?		
Polypropylene bags	4	13.33
On-ground/heap	4	13.33
Jute bags	3	10.00
Gotera	19	63.33
Hermetic bags	0	
What quantity of *berbere* can each storage structure/unit hold? (kg)		
<100	7	23.3
100-500	15	50.0
500-100	2	6.66
>1000	6	20
How much *berbere* do you store normally (on an annual basis, per year)? (kg)		
<100	0	
100-500	25	83.3
500-100	5	6.66
>1000	0	
Where is your *berbere* storage facility located?		
On the field	5	16.66
Within the home	17	56.66
Both (on the field and within the home)	0	
Depends on others to store it	6	20
For how many months (s) do you store your *berbere*?		
One month	1	3.33
Two months	5	16.66
Three months	4	13.33
Four months	7	23.33
Five months	10	33.33
Six months	3	10.00
Do you find any signs of fungal growth in the stored *berbere*?		
Yes	8	26.6
No	20	66.6
I don't know	2	6.66
Do you know anything about mycotoxins?		
Yes	**0**	
No	30	100
Do you face other problems such as insect/pest damage which cause damage or losses after harvest or during storage of your dry *berbere*?		
Yes	0	
No	30	100
Do you add any chemicals/preservative to your stored *berbere* to reduce postharvest losses?		
Yes	0	
No	30	100
Do you do any other practices to help maintain the quality of your stored *berbere*?		
Yes	0	
No	30	100
Purpose of hot red chilli production		
Home Consumption	0	
Sales	1	3.33
Both	29	96.99
What do you want to know more about regarding your *berbere*?		
Factors of deterioration,	30	100
Extending the shelf life/storage	30	100
Quality and weed management	30	100

interviewed ranged in age from 27 to 60 years. The maximum education qualification obtained by any of the assemblers interviewed was 12th grade (equivalent to high school) (10% of respondents). While 40% of the assemblers had studied to standard 10 (10 years of basic education), and 20% had achieved a basic school education. The *kebeles* which the assemblers based in Bure city purchase and collect *berbere* from include *Zalema, Debun, Wadera, Alefa, Beso, Arebajero, Medro, Gelebed, Gulum, Wadero, Dejen, Bure, Tengea and Tataya.*

All the assemblers in the study area collect the *berbere* pods after they have been sun-dried by the farmers. If *berbere* were purchased fresh from farmers, then the assemblers would undertake sun-drying of the *berbere* after spreading it directly on the ground for 7–20 days. Just two assemblers said they might place the *berbere* on a plastic sheet to dry.

The purchased b*erbere* may be stored by the assemblers for periods ranging from 15 days to 2 years. However, only very small quantities of the *berbere* are stored for longer durations as the majority (60%) of assemblers sell their *berbere* immediately to the next-level purchasers. About 60% of the assemblers pack their *berbere* in jute bags, while 20% pack the product in woven polypropylene bags (Fig. 2F). The other 20% of assemblers store their *berbere* in heaps on the floor of a store room (Fig. 2G). All the storage structures are simple rooms constructed with locally available materials (i.e., wood and mud walls, metal sheets, plastic sheets) without any controls for temperature or relative humidity. One assembler reported using both jute and hermetic bags to store *berbere* in. Different varieties of *berbere* are stored in separate containers from each other.

All the assemblers sort the *berbere* before purchasing it from the farmers. The majority remove dirty, discoloured or white coloured, spoiled, broken pods and any plant debris (Fig. 2H). Around 30% of the assemblers clean and grade the *berbere* pods into first, second and third quality classes. The properties the assemblers check for when grading the *berbere* are colour, larger-sized pods, dryness (moisture content), pungency, and absence of contaminants and impurities. It was observed during the survey that sorting by assemblers typically takes place manually with the *berbere* spread on the ground.

About 70% of the assemblers reported observing fungal infection on their *berbere* during storage. The majority of the assemblers confirmed that after two or three months of storage if there is high humidity in the environment, they observe fungal growth. Two respondents explained that when *berbere* was stored for one year or more, it suffered from spoilage. None of the assemblers used fungicides to extend the shelf life of *berbere*. None of the assemblers possessed any cold storage, nor any devices for determining the colour, moisture content and other quality properties.

None of the assemblers had any knowledge or awareness about mycotoxins. Around 70% of the assemblers did not use any formal quality control determination procedures at the time of purchasing the *berbere* from the farmers. While 30% relied on their own experience to judge quality-related factors such as moisture content, absence of impurities, pod size and good pod colour. Around 90% of the assemblers practice re-drying of the *berbere* pods in the sun for one to seven days in the middle of the storage period. Only 20% of the respondents used plastic sheets for drying the *berbere*, while the others spread the *berbere* directly on the ground.

3.3. Berbere handling at the wholesale level

The wholesalers purchase *berbere* directly from the farmers as well as from the assemblers in the different *berbere* production locations around Bahir Dar city, such as Bure, Chagni, Zegem, and Wade locations. The wholesalers are located in the Bahir Dar city vegetable market and sell their *berbere* to retailers, local industry people and households for domestic processing (Fig. 3A). Of the ten wholesalers who were interviewed, eight were male. Most (60%) of these wholesalers did not have any formal education; although two of the ten wholesalers interviewed were diploma holders. The wholesalers interviewed reported determining the quality of the *berbere* at the assembler's or farmer's stage by both visual and manual handling inspection of the *berbere* pods before purchasing them. These wholesalers typically purchase between 300 and 4,000 kg of *berbere* at a time.

While two of the wholesalers interviewed reported selling on the *berbere* they purchase almost immediately. The majority reported typically storing it for three to eight days before starting to sell it, this was usually due to them trying to clear their old stock before they started selling the newly acquired produce. No device or formally agreed methods are used by the wholesalers for determining the moisture content or the quality of the *berbere*. The *berbere* is typically stored by the wholesalers in sheds without any temperature or relative humidity control (Fig. 3B and C). At the wholesale stage in the value chain, the

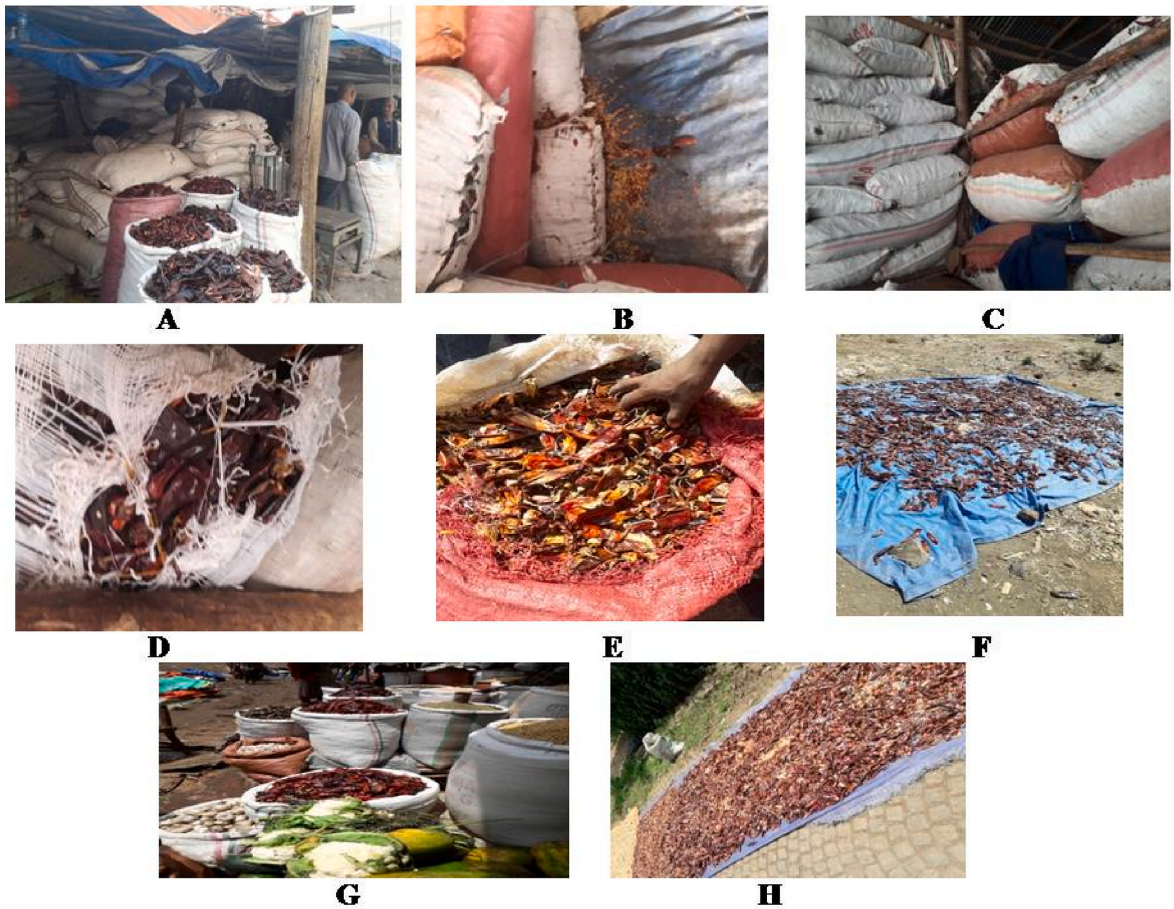

Fig. 3. *Berbere* handling at wholesalers and retailer levels in Bahir Dar city, Ethiopia.
(A) *Berbere* pods on display at the wholesale market level. (B, C) Storage of the *berbere* pods in stacks of woven polypropylene bags. (D) Example of holes in damaged bags of stored *berbere* following sampling to check the quality of the stored produce. (E) Sorted *berbere* at the wholesale level. (F) *Berbere* is sun-dried on plastic sheeting at the wholesale level. (G) Retail marketing of *berbere* alongside other spices and vegetables. (H) Drying of the *berbere* at retailer levels.

berbere is typically packed in woven polypropylene bags, with each of the bags having a hole in it which has been made by and is used for taking samples from it to check the quality of the *berbere* (Fig. 3D). These holes are not closed again after sampling.

No practice of adding moisture to the *berbere* to increase its weight was reported during the current survey. The wholesalers reported observing fungal growth on the *berbere* pods they had procured, and that in the rainy seasons there is an increase in the moisture content of the *berbere* and the pod colour may change with white or black spots being observed due to the growth of fungus on it. The wholesalers reported that when high levels of spoilage occur they then discard the *berbere*, but if the spoilage is limited, they sort out the spoiled pods and sun-dry the rest in the open (Fig. 3E and F). All of the wholesalers interviewed, reported manually sorting the *berbere* before selling it on. They do this to sort out pods with white on them, broken and small pods and plant debris. The majority of the wholesalers (70%) said they sun-dry their *berbere* stocks for one to three days if they observe fungal spoilage. Just over half of them report using plastic sheets to sun-dry the pods on, while the rest dry the *berbere* directly on the ground.

3.4. Berbere handling at the retailer level

Within Bahir Dar city, there are several small retail markets located in different locations (Fig. 3 G). About 70% of the retailer respondents were female. With the youngest respondent being 29 years and the oldest 60 years old. Two of the ten retailers interviewed had no formal education, the rest had attended school between 5th and 12th grade, and one had a Bachelor's degree. All of the retailers purchased their *berbere* from wholesalers, with two of them also occasionally purchasing directly from farmers. Retailers tend to purchase 50–200 kg of *berbere* at a time.

About 30% of the retailers reported that they start selling the *berbere* immediately after they have procured it. While a few typically store their *berbere* for between 1 day and a week before starting to sell it. The retailers interviewed do not have any devices or methods for objectively determining the moisture content. In the case of *berbere* quality determination at the retailer level, 100% of the retailers said they check the sample by touch, and use visual observation and direct interaction with the wholesalers regarding the quality, origin and other issues. Around 30% of the retailer respondents had not observed the presence of fungal growth on the *berbere*. While 70% of retailers said they sort out the spoiled *berbere* and discard the spoiled pods. About 40% of the retailers reported that they do sun-dry the *berbere,* typically for 1–2 days if the moisture content was perceived to be high. This sun-drying is typically done on plastic sheets (Fig. 3H).

The majority of the retailers sell their products to domestic processers or local retail shops, with a few selling to industrial processors. All the retailers explained that the customers inspect the quality of the *berbere* before they purchase, and concentrate on the colour, whether it is free of contaminants, the pod size, the absence of white discoloured *berbere*, and whether it has a good pungency. Only a few consumers enquire about the variety and origin of the *berbere*. Most of the retailers sell their *berbere* divided into three quality categories: high, medium, and low. While 40% just sell a single quality of the *berbere*.

3.5. Berbere handling during domestic household processing into powder

The age of the domestic household processors interviewed ranged from 26 to 54 years. All of them were female and educated, with the minimum education level being 12th standard and the maximum being a Master's Degree, 50% of the respondents were Bachelor's degree holders. All the respondents purchase *berbere* pods from Bahir Dar local market to prepare the *berbere* powder. Most of the respondents (60%) purchase *berbere* pods in dried form, while the others (40%) purchase them in fresh form. All the respondents consider the quality of the pods before purchasing. In the case of dried *berbere*, visual observation and manual touching were used to inspect the quality, and the respondents looked for a whole undamaged pod with thick skin and no discolouration (white patches), no plant debris, and with good pungency. Fresh pods were also inspected visually and manually for colour, weight and absence of spoilage. No instrumentation for checking moisture content was used.

The respondents purchase between 10 kg and 30 kg to prepare *berbere* powder depending on their family size and consumption patterns. Most of the respondents (90%), store the *berbere* powder they have prepared for up to one year. All the respondents prepare the *berbere* just once per year, typically between November and January, and then they use it for the rest of the year. Around 70% of these respondents had observed fungal growth on and inside the *berbere* pods, describing it as discolouration, or the presence of a black powder/dust inside the pod. Where fungal growth was observed, the respondents sort the sample and remove the infected portion and still use the remaining part. If the incidence of fungal growth is high, 40% of respondents said they discard the *berbere*. While one respondent reported that if spoilage is high they may return the *berbere* to the seller. All the respondents sort the purchased *berbere* and remove any white and black discoloured pods, plant debris or dirt. Of the respondents, 80% said they had no knowledge about mycotoxins. The 20% of respondents who were aware of mycotoxins, explained that mycotoxins are responsible for cancers and other negative health impacts. The respondents who knew about mycotoxins and their effects were those with Masters' level education.

All the respondents mix other local spices with the *berbere* and use small-scale commercial milling establishments to prepare *berbere* powder. The type and proportions of the spices depend on their experience and traditional practices. The other spices used are garlic, ginger, rue (*Ruta chalepensis)*, cinnamon (*Cinnamomum zelani)*, kurunfid (*Aframomum corrorima)*, clove, and black pepper. The wet spices such as ginger and garlic are crushed separately and dried in the sun and added to *berbere* pods before grinding (Fig. 4A and B). Salt is also added by all the respondents. All the respondents reported that the spices are added for taste purposes. Additionally, around 30% of respondents said the other spices are also added as preservatives, 20% of respondents said the other spices have certain health benefits, and 20% of respondents said they help reduce the hotness/burning effect of the *berbere* powder.

About 70% of the domestic *berbere* processing respondents reported some spoilage of the processed *berbere* powder occurs as the storage duration increases, with spoiled *berbere* powder forming lumps and the taste and colour of it changing. To avoid spoilage, the respondents said they pack the *berbere* powder in airtight containers, to reduce its exposure to air and moisture. A few respondents explained that if spoilage occurs, the spoiled portion will be removed and the remaining portion will be used. While other respondents said they would discard all the *berbere* powder if any spoilage occurred. Around 70% of the respondents reported that they do not practice any re-drying of the *berbere* powder during the storage period. While a few respondents said that if they find any changes, the *berbere* powder will be sun-dried for one day (10% of respondents), or that they re-dry the *berbere* powder for 2–3 days in the sunlight after it has been stored for about 6 months (20% of respondents), and this is particularly the case in the rainy season.

3.6. Berbere handling at the industrial processing level

All the industrial processors surveyed were small-scale/cottage industries. Fifty per cent of the industrial processors interviewed were male. Most (70%) of the industrial *berbere* powder processors procure

Fig. 4. *Berbere* postharvest handling at the domestic processors' level.
(A) *Berbere* pods spread on plastic sheets at a domestic processor. (B) Sun-drying of *berbere* and different spices on plastic sheets at the domestic processor level. (C) The mill used for *berbere* powder preparation (used by both industrial and domestic processors). (D) A packet of *berbere* powder on sale in the market. (E) Lose *berbere* powder on sale at the market.

their raw material (*berbere* pods) from wholesalers in the Bahir Dar city local market. The remaining 30% of respondents collect *berbere* pods directly from assemblers and farmers in different production locations depending on their contacts.

Regarding the type of *berbere* procured, 60% of the respondents purchased dry *berbere* pods while the remaining 40% purchase fresh pods. Those who purchase fresh *berbere* pods do so in amounts of around 150–200 kg each time. This may be because fresh *berbere* requires quite a large space for drying so, they cannot procure higher amounts. The industrial processors who purchase the dry *berbere*, procure batches of 300–3000 kg. These amounts depend on the processor's storage, processing and human resource capacities.

The processors store the *berbere* for between 2 and 15 days. Prior to starting to process the *berbere* pods, the industrial processors sort them to remove the white-coloured pods, tips/broken pieces, dust, and plant debris. Despite these practices, the majority (70%) said they did not use any quality control or quality management systems. The remaining 30% use a quality control process involving visual checking of dryness and cleanliness at each step but no use of any analytical instruments. After purchasing the *berbere* pods, all the processors sun-dry them. The duration of the sun-drying ranges from two days to one week depending on the moisture content of the *berbere* pods and weather conditions.

During the processing of the *berbere* powder around 90% of respondents add different spices and salt in different concentrations. After milling, the colour, smell, taste, smoothness/fineness and visual appearance of the *berbere* powder will be checked. Following milling, the *berbere* powder is packed in 250 g, 500 g or 1 kg packets for sale in the local markets (Fig. 4D). The quantities of *berbere* produced varied between these industrial processors from 100 kg/week to 300 kg/day. Following the packing of the *berbere* powder product, it is released to the market within one to three weeks depending on the demand.

3.7. Water activity and mycotoxins occurrence

The seasonal calendar for the production and processing of *berbere* in Bure district, Amhara region, Ethiopia is presented in Table 6. The incidence of aflatoxin and ochratoxin and water activity (aw) in the *berbere* pod and powder samples collected during the survey are presented in Table 7. All the samples tested positive for both aflatoxins and ochratoxins, meaning they contained levels higher than the maximum tolerable levels (>20 ppb and >2 ppb, respectively) set for both aflatoxin and ochratoxin in *berbere* by different regulatory bodies (Supplementary Information Table 2). The aw of the *berbere* samples collected from farmers ranged from 0.59 to 0.75 corresponding to moisture contents of 10–18% (Supplementary Information Table 1).

In the case of assembler samples, all samples tested positive for the presence of aflatoxins and ochratoxins. Water activity of the samples at assembler-level ranged from aw 0.58–0.71. Typically, aw value for dehydrated vegetables should be aw < 0.60 (mould growth starts when aw is above 0.60). This shows that several of the tested samples had a higher *aw* than recommended to control mould growth.

All the samples tested at wholesaler level also showed the presence of the studied mycotoxins. The water activity of 0.55–0.72 was reported for the *berbere* pod samples collected from the wholesale level. No control

Table 7
Presence of aflatoxins, ochratoxins and water activity in *berbere* samples collected from different stages of the value chain in Bure district, Amhara region, Ethiopia.

Sample location	No. of samples	% of samples testing positive for		Range of water activity (Aw)
		Aflatoxin	*Ochratoxin*	
Farmers	30	100	100	0.59–0.75
Assemblers	10	100	100	0.58–0.71
Wholesalers	10	100	100	0.55–0.72
Retailers	10	100	100	0.51–0.75
Industrial processors	20	100	100	0.41–0.73(Pods) 0.42–0.53 (Powder)
Berbere powder in market	10	100	100	0.49–0.61
Berbere powder from homes/domestic	10	100	100	0.42–0.59
Total samples	**100**	**100**	**100**	

Table 6
Seasonal calendar for production and processing of *berbere* in Bure district, Amhara region, Ethiopia.

Months	***Mar***	***Apr***	***May***	***Jun***	***Jul***	***Aug***	***Sep***	***Oct***	***Nov***	***Dec***	***Jan***	***Feb***
Seasons	Autumn (*Belg*/ short rainy season)			The rainy season (*Meher*)			Harvest season (*Tseday*)			Dry season (*Bega*)		
Precipitation (mm)	74.2	83.9	70.2	56.7	237.5	255.7	111.1	41.8	27.6	19.7	19.7	18.7
Temperature °C (min/max)	13/27	15/28	15/29	16/30	16/28	15/27	15/27	12/26	11/25	10/24	11/25	11/27
Chilli planting				■	■							
Harvesting of fresh chilli									■	■		
Household processing									■	■		

over the temperatures and relative humidity occurs in the wholesaler's storage warehouses and units. Nor are there any pest control, fungal control, or rodent control activities which occur for *berbere* after harvest. Poor hygiene during handling and storage was observed. Re-drying of *berbere* at the market places was reported, these crowded places are dusty and may contain fungal spores which may cause contamination during the re-drying of the *berbere*.

All of the samples collected from the retailers also tested positive for both mycotoxins. The water activity was similar to that in the wholesaler's samples at 0.51–0.75. The retailers reported noticing fungal infection in *berbere* pods.

Similarly, all the dry pods and processed *berbere* powder at the industrial processor level tested positive for both toxins. The pods had a water activity of 0.41–0.73 and the prepared *berbere* powder 0.42–0.53. The reduced water activity in the powder is attributed to the application of the sun-drying method. The water activity in the *berbere* pods is similar to that in the *berbere* samples from the farmers, assemblers, wholesalers and retailer levels.

A relatively low water activity of 0.49–0.61 was observed in the *berbere* powder collected from the market compared to the *berbere* pods (aw 0.41–0.73). However, all the market samples were positive for both toxins. The *berbere* powder collected from the market is packed in individual low-density polyethylene packets with limited samples available loose or packed in large plastic bags and exposed to the open environment/dust (Fig. 4E).

When samples of *berbere* powder were taken from homes, the water activity in them was 0.42–0.59, and all the samples tested positive for the presence of both toxins. The usage of the spices, poor hygiene, usage of community mills (Fig. 4C) and the *berbere* pods already positive for both toxins at all stages from farmer to retailer levels contribute to the presence of mycotoxins in *berbere* powder at the processor stage.

4. Discussion

4.1. Farm-level berbere production

This study revealed several important aspects of *berbere* cultivation among the responding farmers. The mean area of *berbere* cultivated per household was 0.65 ha, and ranged from 0.25 ha to 2 ha. These findings align with a previous study by Abebe and Abera (2019) which reported that *berbere* cultivation in Bure is typically carried out on land areas of less than 1 ha. The majority of respondents rely on natural rainfall and practice rain-fed *berbere* production, while a smaller proportion practiced both rain-fed and irrigated production.

The preferred variety of *berbere* grown by the respondents was the Danbure variety, with only a few cultivating the Mareko Fana variety. This finding contrasts with an earlier report by Tesheshigo et al. (2019), which indicated that Mareko Fana was the main *berbere* variety cultivated in Bure. The study by Tesheshigo et al. (2019) also provided valuable insights into the harvesting timeline (150 days after planting), marketable yield (6.3 t/ha) and average plant height (69.33 cm) of the Mareko Fana variety. Work by Gobie (2019) also found harvesting took place 5–6 months after planting but was directly dependent on the climate, agriculture practices performed, and the variety grown.

Pests and diseases were reported as a significant challenge by more than half of the farmers. Bacterial spot (*Xanthomonas campestris*), powdery mildew (*Leveillula Taurica*), and wilt/root rot (*Fusarium oxysporum*) have been identified as the predominant disease problems in *berbere* cultivation in the Bure district (Abebe and Abera, 2019).

Weed infestation was also reported by 50% of the respondents, which is consistent with the understanding that weeds can negatively impact *berbere* plant growth and yield (Adenubi and Sanni, 2020). Many weed management methods exist, including manual removal and chemical spraying, however, availability of such chemicals in low-income countries such as Ethiopia is often limited. Tesfa et al., (2017) reported that in some locations farmers believe that weeding immediately following a rain shower or on cloudy days will favour a powdery mildew outbreak. However, limited availability of herbicides and sprayers in low-income countries such as Ethiopia add labour challenges for farmers needing to control weeds.

Crop rotation was practiced by around 70% of the respondents, indicating their awareness of the benefits of alternating crops on the same piece of land. However, the remaining 30% reported continuous cultivation of *berbere* on the same land. It has been suggested this continuous cultivation may be influenced by the increased market price of the commodity (Shumeta, 2012).

Rainfall played a crucial role in the various stages of *berbere* cultivation. The majority of respondents reported rainfall during flowering, pod maturation, and harvesting. This aligns with the findings of Djomo et al. (2020) and Dahiru and Tanko (2018), who highlighted the impact of climate variations and rainy seasons on crops, including *berbere*. Rainfall during the drying process was reported by 70% of the respondents, this can lead to prolonged drying periods and quality deterioration of *berbere* pods (Hempattarasuwan et al., 2020).

4.2. Farmers' drying, sorting and storage of berbere

Sun-drying was the predominant drying method employed by virtually all the farmers. A moisture content of less than 10% is recommended for optimal shelf-life of *berbere* pods (Prakash and Eipeson, 2003). Sun-drying *berbere* pods under uncontrolled conditions can due to prolonged sunlight exposure, lead to challenges such as bleaching and dull colour formation. Additionally, sun-drying directly on the ground may result in contamination with foreign matter or infestation by insects and fungi, which thrive in moist conditions, thereby reducing the quality and safety of the *berbere* (Prakash and Eipeson, 2003; Fudholi et al., 2013).

In recent years, various types of solar and artificial dryers have been developed across the world (Paul and Singh, 2013). Artificial dryers were shown by Gupta et al., (2018) to be better at maintaining *berbere* pod quality than traditional sun-drying methods. However, such advanced drying equipment is not readily available or affordable to farmers in the study area.

It is worth noting that 53% of the farmers reported observing fungal infections or diseases on the pods while still in the field before harvesting, supporting research by Abebe and Abera (2019) that highlighted the prevalence of fungal diseases in *berbere* in the West Gojjam zone of Ethiopia. Regarding sorting, the majority of the farmers (70%) practiced post-drying sorting. During this stage, spoiled, broken, and pale or white-coloured *berbere* pods were sorted out, while plant waste and dust were removed. This practice of post-drying sorting is similar to practices observed among chilli farmers in India (Pruthi, 2003).

Most of the farmers used *goteras* for *berbere* storage, as is commonly done for preserving spices in Ethiopia (Tesfa et al., 2017). While in many places' plastic bags (polyethylene) are commonly used for packing dried *berbere* (Yanti et al., 2018), in India, jute bags or gunny bags are used for chilli pepper storage (Peter et al., 2003). The environmental conditions, specifically temperature and humidity, within the storage containers play a crucial role in maintaining *berbere* quality. However, insect pests can cause damage during storage, and fumigation has been suggested as a control measure (Yogeesbh and Gowda, 2003). The mean storage duration reported by the farmers in this study was 3.9 months, but individual farmers stored *berbere* for varying durations. Fungal growth during storage is a common issue when the moisture content of the *berbere* pods increases (Yogeesbh and Gowda, 2003), and previous studies have identified fungal species such as *Aspergillus* sp., *Rhizopus* sp., and *Penicillium* sp. as potential contaminants (Mandeel, 2005). However, none of the farmers in the current study reported awareness of mycotoxins, highlighting the need for knowledge and awareness among *berbere* handlers throughout the value chain to prevent their development (Udomkun et al., 2018).

Interestingly, none of the farmers reported pest or disease issues causing losses after harvest or during storage of *berbere*. Farmers attribute this to the natural insect deterrent qualities of the red chilli peppers (Swamy and Wesley, 2017). It is noteworthy that none of the farmers used any storage protectants or other practices to protect and maintain the quality of their stored *berbere*.

Postharvest knowledge for *berbere* is currently predominantly flowing through traditional information pathways, for example, learning from elders or friends, with only 7% of farmer respondents mentioning having learnt about *berbere* postharvest aspects from agricultural officers. Demands for more information about the causes of and methods for reducing postharvest quality deterioration of *berbere* were expressed.

4.3. Berbere handling by assemblers, wholesalers and retailers

The assemblers play an important role in the *berbere* value chain serving as intermediaries collecting and purchasing *berbere* from farmers from different villages for resale to wholesalers and retailers. Work by Shumeta (2012) reported from Southwest Ethiopia that individual assemblers collect approximately 50–120 quintals (1 quintal = 100 kg) of *berbere* pre year and resell it to wholesalers across various regions in Ethiopia.

Although most assemblers aim to sell their *berbere* on immediately to the next-level purchasers, some do store it for periods ranging from 15 days to 2 years. They may re-dry it during this period using open air sun-drying with the same contamination risks as occur during open-air on ground sun-drying at farmers'-level. If the moisture content is high, even temporary storage of *berbere* can result in quality deterioration and fungal growth and can lead to the production of mycotoxins (Peter et al., 2003). In different regions of Ethiopia, handlers have been observed using floor storage or heap storage for *berbere* pods before packing them into various types of bags (Kuchi et al., 2014). The majority of assemblers remove dirty, discoloured, spoiled, broken pods, and any plant debris, by winnowing outside and manually sorting.

Wholesalers play a crucial role in the *berbere* value chain, purchasing *berbere* from farmers and assemblers and supplying it to retailers, local industries, and households (Gobie, 2019; Shumeta, 2012b). The quantities of *berbere* purchased by each wholesaler interviewed in the current study range from 300 to 4,000 kg per trader per year, which aligns with earlier findings by Shumeta (2012a) where procurement quantities were influenced by population, seasonal variation, and market demand. The wholesalers did not report using any chemical preservatives or other materials to reduce fungal growth problems in their stored *berbere*, and none of them were aware of mycotoxins. They sort and re-dry their produce, discarding any spoiled *berbere* pods*, and* were aware that during the rainy season increased fungal growth occurs on the *berbere* pods. A lack of formal quality assessment practices exists and the storage facilities are unable to control the temperature and humidity conditions which can potentially impact the quality and safety of *berbere* during this stage of the value chain.

Retailers also play a crucial role in the value chain by selling *berbere* directly to customers, local retail shops and industrial processors. They rarely store *berbere* for more than a week. Some retailers explained they had observed fungal growth on *berbere* pods, particularly during the rainy seasons, manifesting as black and white spots on the outside or black dust inside the pods. In cases of high spoilage, one retailer mentioned selling the product at a lower price to consumers, while two other retailers stated that they would return the product to the wholesaler. Retailers reported re-sun-drying the *berbere*, typically on plastic sheets, if the moisture content was too high. Customers are reported to inspect the *berbere,* particularly the pod colour and check for any visible contamination before buying it.

4.4. Domestic and industrial processing

Regarding domestic household processors, the respondents explained that they purchase the *berbere* just after harvest during the peak of its abundance in the markets, when prices are most reasonable (Gobie, 2019). This practice ensures that the *berbere* used for processing is of high quality and freshness, which is crucial for the overall flavour and aroma of the final *berbere* powder.

The shelf life of *berbere* powder depends on various factors, including the methods employed in pre-processing, processing, storage conditions, and the antioxidant composition of the *berbere* (Pruthi, 2003). Microbial contamination of the *berbere* and susceptibility to spoilage once ground are issues of concern to domestic processors. Ground *berbere* is more prone to spoilage (Buckenhuskes, 2003). This highlights the need for appropriate handling and storage practices throughout the value chain to maximize the shelf-life and quality and minimize the risk of microbial contamination and subsequent spoilage during the processing and storage of *berbere* powder by processors, food service providers or consumers.

The results indicate that small-scale or cottage industries involved in *berbere* production rely on traditional methods and subjective assessments for quality control, with limited use of technical instruments or formal quality management systems. The lack of temperature, moisture or rodent control in storage facilities raises concerns about product integrity and potential spoilage. Implementing appropriate handling practices and storage conditions could help mitigate the risk of microbial growth and maintain the overall quality of the *berbere*. Increasing awareness and implementing mycotoxin control measures would be beneficial to ensure the safety of the *berbere* products.

4.5. Water activity and mycotoxins occurrence

Water activity (aw) is a critical factor affecting fungal growth and mycotoxin production. The most favourable growth conditions for *Aspergillus flavus*, a fungus associated with aflatoxin production, are within a temperature range of 25–30 °C and *aw* higher than 0.970 (Chuaysrinule et al., 2020). Respondents in the current study noted that when *berbere* were not properly dry (high moisture content) it encourages fungal growth. The relationship between water activity and moisture content in preserving *berbere* is described by Shirkole and Sutar (2018) and Pruthi (2003). Shirkole and Sutar (2018) report that a water activity of 0.4199 corresponds to a moisture content of 6.93%, while Pruthi (2003) suggests a moisture content of around 10% (aw 0.59) is optimal for *berbere* pod preservation.

The sun-drying method commonly used by *berbere* farmers, whereby pods are spread directly on the ground, can lead to fungal contamination. The correlation between sun-drying duration and aflatoxin formation in red-chillies has been reported previously by Sahar et al., (2017). The rainy season poses additional challenges, as heavy rains and moisture re-absorption can increase the risk of fungal contamination. Moreover, poor weed management is reported to contribute to termites, pest development, pod damage, and *Aspergillus* infection (ICRISAT, 2016; Tadesse, 2009).

The current study found a lack of knowledge and awareness among farmers and processors regarding mycotoxins. Training and education are deemed crucial for effective management of aflatoxin problems (Udomkun et al., 2018), and the adoption of improved agricultural practices, including effective weed and pest management is crucial to mitigate mycotoxin contamination in *berbere* (Kimanya and Mlalila, 2020).

Storage and postharvest handling practices also contribute to mycotoxin contamination. The poor storage structures and methods used at the different levels in the *berbere* value chain, illustrate the lack of mechanisms for controlling environmental conditions. The absence of moisture content analysis and the inadequate implementation of insect pest and fungal management strategies were also important factors. Previous studies on red chilli peppers have highlighted how technologies such as cold storage, radiation, vacuum packing, and hermetic bags can control fungal growth and maintain quality (Ravi Kiran et al., 2005; Onyenekwe and GH, 1995; Chetti et al., 2014; Abrar et al., 2023).

Table 8
Overview of research findings on aflatoxin and ochratoxin presence in *berbere*/dry red-hot chilli and related products across different countries.

Country	No. of samples	% of samples testing positive for		Reference
		Aflatoxin	*Ochratoxin*	
Spain	21	90 (AFT B1)	67	(Hierro et al., (2008)
India	55	85.5	72.2	Jeswal & Kumar, (2015)
India	25	52.7	40	Jeswal & Kumar, (2016)
India	40	85.45	72.7	Jeswal & Kumar, (2014)
Sri Lanka	86	75	40	Yogendrarajah et al., (2014)
Belgium	35	35	45	Yogendrarajah et al., (2014)
USA	169	64%	–	Singh & Cotty, (2017)
Nigeria	55	93%	–	Singh & Cotty, (2017)
Pakistan	331	48.33	–	Khan et al., (2014)
Pakistan	176	66	–	Shamsuddin et al., (1995)
Pakistan	312	–	40.4%	Iqbal et al., (2017)
Pakistan	13	100	–	Paterson (2007)
Turkey	25	72	–	Yilmaz (2017)
Turkey	120	62.5%	–	Set & Erkmen, (2014)
Turkey	125	65.7	–	Ankara, (2012)
Nigeria	70	69	–	Ezekiel et al., (2019)
Ethiopia	60	8.33%	–	Fufa & Urga,1996
Ethiopia	135	47	–	Tsehaynesh et al., (2021)
Malaysia	80	65	81.25	Jalili & Jinap, (2012)
Italy	30	–	40.0	Prelle et al., (2013)l
Italy	130	–	78.9%	Prelle et al., (2014)

However, none of these technologies are used in the study location currently and the affordability of several of them may be challenging for most of the value chain actors.

Contamination during milling may also occur due to inadequate hygiene practices. The addition of other spices, such as dried ginger and garlic, could also potentially introduce fungal toxins into the *berbere* powder (Hacibekiroğlu & Kolak, 2013; Hammami et al., 2014; Macdonald and Castle, 1996). An overview of previous research findings on aflatoxin and ochratoxin presence in red-chilli pepper is summarised in Table 8.

4.6. Conclusions and recommendations

In conclusion, this study revealed that all the *berbere* samples tested positive for aflatoxin and ochratoxin, indicating the widespread presence of these mycotoxins. The findings also highlighted the continued use of traditional agricultural practices in *berbere* cultivation and handling within the Amhara region of Ethiopia. Factors such as rain-fed cultivation, exposure to rain during growth stages, poor weed management, absence of pesticide applications, sun-drying directly on the ground, inadequate storage structures, low-quality packing materials, and the absence of formal quality control methods were identified as contributors to reduced quality and mycotoxin contamination throughout the *berbere* value chain. The packing materials are also poor quality and damaged. No formal method nor analytical devices are used to determine the moisture and any other quality parameter at any stage of the domestic *berbere* value chain. In Ethiopia, the *berbere* pods are converted into a powder and different spices are added. At the industrial *berbere* processor scale, there are no formal quality control systems being implemented. We conclude that poor handling practices in the value chain contribute to the presence of aflatoxins and ochratoxins in all the *berbere* samples tested in this study. At all stages, the training of actors is poor, but they are eager to have their capacity strengthened.

Potential recommendations to improve the quality of and reduce the mycotoxin contamination of *berbere*, include:

- Working with the value chain actors to co-develop, promote and test the use of an integrated pest management system for the *berbere* crop, including:
- Practising irrigated cultivation for suitable *berbere* varieties
- Regular weed management using a range of appropriate methods and training
- Improved drying of *berbere* on plastic sheets, and for some actors artificial dryers to support faster and more uniform drying in hygienic conditions to maintain quality
- Training of the different value chain actors on the use of good hygiene practices
- Training of the different value chain actors on sorting, handling and storage, quality management practices, and implementation of quality control systems in *berbere* industries
- Use of simple moisture determination facilities at all stages of the value chain
- Use of good packing bags and materials
- Use of appropriate storage facilities at each value chain step.
- Supporting greater awareness and knowledge about the spoilage factors and the importance of managing mycotoxins in *berbere* industries
- Drafting and supporting regulations to enable government agencies to monitor and support the implementation and achievement of standards in *berbere* powder handling and processing in domestic value chains.

CRediT author statement

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Declaration of competing interest

The authors declare that they have no conflicts of interest.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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References

Abebayehu, A., Misginaw, T., Abraham, B., Solomon, T., Alemayehu, R., Bayu, D., 2014. Influences of mineral nitrogen and phosphorous fertilization on yield and yield contributing components in hot pepper (*Capsicum annuum* L.). Afr. J. Agric. Res. 9 (7), 670–675. https://doi.org/10.5897/ajar2013.8262.

Abebe, A., Abera, M., 2019. Pepper disease assessment and identification in major growing districts of west Gojam zone in northwestern Ethiopia. Int. J. Sustain. Agric. Res. 6 (1), 8–20. https://doi.org/10.18488/journal.70.2019.61.8.20.

Abrar, M., Ahsan, S., Nadeem, M., Liaqat, A., Chughtai, M.F.J., Farooq, M.A., Mehmood, T., Khaliq, A., Siddiqa, A., 2023. Detection and quantification of aflatoxins in spices stored in different food packaging materials. J. Stored Prod. Res. 101, 102081.

Adenubi, O., Sanni, K., 2020. Weed interference and fruit yield of chilli Pepper (Capsicum Annum) as influenced by plant density. Open J. Polit. Sci. 5 (1), 30–32. https://doi.org/10.17352/ojps.000020.

Ankara, E.-., 2012. Original article investigation of aflatoxin bx levels in red pepper. Turkish Journal of Pharmaceutical Sciences 9 (3), 293–300.

Arimboor, R., Natarajan, R.B., Menon, K.R., Chandrasekhar, L.P., Moorkoth, V., 2015. Red pepper (Capsicum annuum) carotenoids as a source of natural food colors: analysis and stability—a review. J. Food Sci. Technol. 52 (3), 1258–1271. https://doi.org/10.1007/s13197-014-1260-7.

Boseland, P.W., Votava, E.J., 2000. Pepper: Vegetable and Spice Capsicum. CABI Publishing, New York, pp. 1–16.

Buckenhuskes, H.J., 2003. Current requirements on paprika for food industry. In: Amit, Krishna De (Ed.), Capsicum the Genus Capsicum. Taylor & Francis, New York, pp. 223–230.

Chakrabarty, S., Islam, M., Islam, A., 2017. Fundamental and applied agriculture nutritional benefits and pharmaceutical potentialities ofchillies: a review. Fundamental and Applied Agriculture 2 (2), 227–232. Retrieved from. https://www.ars.usda.gov.

Chetti, M.B., Deepa, G.T., Antony, R.T., Khetagoudar, M.C., Uppar, D.S., Navalgatti, C. M., 2014. Influence of vacuum packaging and long term storage on quality of whole chillies (Capsicum annuum L.). J. Food Sci. Technol. 51 (10), 2827–2832. https://doi.org/10.1007/s13197-012-0763-3.

Chopan, M., Littenberg, B., 2017. The association of hot red *berbere* pepper consumption and mortality: a large population-based cohort study. PLoS One 12 (1), 1–10. https://doi.org/10.1371/journal.pone.0169876.

Chuaysrinule, C., Mahakarnchanakul, W., Maneeboon, T., 2020. Comparative study on the effect of temperature and water activity on *Aspergillus flavus* and *Aspergillus carbonarius* isolates growth and mycotoxin production on a chilli powder medium. Cogent Food Agric. 6 (1), 1782097 https://doi.org/10.1080/23311932.2020.1782097.

Dahiru, T.M., Tanko, H., 2018. The effects of climate change on food crop production in northern Nigeria. International Journal of Reserch 6 (9), 458–469.

Djomo, C.R.F., Ukpe, H.U., Ngo, N.V., Mohamadou, S., Adedze, M., Pemunta, N.V., 2020. Perceived effects of climate change on profit efficiency among small scale chilli pepper marketers in Benue State, Nigeria. Geojournal, 0123456789. https://doi.org/10.1007/s10708-020-10163-x.

Ezekiel, C.N., Ortega-Beltran, A., Oyedeji, E.O., Atehnkeng, J., Kössler, P., Tairu, F., et al., 2019. Aflatoxin in chilli peppers in Nigeria: extent of contamination and control using atoxigenic aspergillus flavus genotypes as biocontrol agents. Toxins 11 (7). https://doi.org/10.3390/toxins11070429.

Fudholi, A., Othman, M.Y., Ruslan, M.H., Sopian, K., 2013. Drying of malaysian capsicum annuum L. (Red chilli) dried by open and solar drying. Int. J. Photoenergy 2013. https://doi.org/10.1155/2013/167895.

Fufa, H., Urga, K., 1996. Screening of aflatoxins in Shiro and ground red pepper in Addis Ababa. Ethiop. Med. J. 34 (4), 243–249.

Gobie, W., 2019. A seminar review on red pepper (Capsicum) production and marketing in Ethiopia. Cogent Food Agric. 5 (1), 1647593 https://doi.org/10.1080/23311932.2019.1647593.

Gupta, S., Sharma, S.R., Mittal, T.C., Jindal, S.K., Gupta, S.K., 2018. Effect of different drying techniques on quality of red powder. Indian J. Ecol. 45 (2), 402–405.

Hacibekiroğlu, I., Kolak, U., 2013. Aflatoxins in various food from Istanbul, Turkey. Food Addit. Contam. Part B Surveillance 6 (4), 260–264. https://doi.org/10.1080/19393210.2013.813080.

Hammami, W., Fiori, S., Al Thani, R., Ali Kali, N., Balmas, V., Migheli, Q., Jaoua, S., 2014. Fungal and aflatoxin contamination of marketed spices. Food Control 37 (1), 177–181. https://doi.org/10.1016/j.foodcont.2013.09.027.

Hempattarasuwan, P., Somsong, P., Duangmal, K., Jaskulski, M., Adamiec, J., Srzednicki, G., 2020. Performance evaluation of parabolic greenhouse-type solar dryer used for drying of cayenne pepper. Dry. Technol. 38 (1–2), 48–54. https://doi.org/10.1080/07373937.2019.1609495.

Hierro, J.M.H., Garcia-Villanova, R.J., Torrero, P.R., Fonseca, I.M.T., 2008. Aflatoxins and ochratoxin a in red paprika for retail sale in Spain: occurrence and evaluation of a simultaneous analytical method. J. Agric. Food Chem. 56 (3), 751–756. https://doi.org/10.1021/jf073002c.

ILRI, 2007. Bure Pilot Learning Woreda Diagnosis, Program Design and Atlas. ILRI, Nairobi, Kenya.

International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), 2016. How to Reduce Aflatoxin Contamination in Groundnuts and Maize. A Guide for Extension Workers. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT).

Iqbal, S.Z., Asi, M.R., Mehmood, Z., Mumtaz, A., Malik, N., 2017. Survey of aflatoxins and ochratoxin A in retail market chilies and chili sauce samples. Food Control 81 (1881), 218–223. https://doi.org/10.1016/j.foodcont.2017.06.012.

Jalili, M., Jinap, S., 2012. Natural occurrence of aflatoxins and ochratoxin A in commercial dried chili. Food Control 24 (1–2), 160–164. https://doi.org/10.1016/j.foodcont.2011.09.020.

Jeswal, P., Kumar, D., 2014. Toxigenic mycofloral association and mycotoxins contamination in turmeric, coriander & red chilli and risk assessment of its effect. American Journal of Biological, Chemical and Pharmaceutical Sciences 2 (2), 2328–6814.

Jeswal, P., Kumar, D., 2015. Mycobiota and natural incidence of aflatoxins, ochratoxin A, and citrinin in Indian spices confirmed by LC-MS/MS. International Journal of Microbiology 2015. https://doi.org/10.1155/2015/242486.

Jeswal, P., Kumar, D., 2016. Mycotoxins and their producing fungi from spices of Bihar (India). Int. J. Bioinf. Biol. Sci. 2 (2), 174–177.

Khan, M.A., Asghar, M.A., Iqbal, J., Ahmed, A., Shamsuddin, Z.A., 2014. Aflatoxins contamination and prevention in red chillies (Capsicum annuum L.) in Pakistan. Food Addit. Contam. Part B Surveillance 7 (1), 1–6. https://doi.org/10.1080/19393210.2013.825330.

Kuchi, V.S., Gupta, R., Kachwaya, D.S., 2014. A review on dehydration of chilli. Plant Archives 14 (2), 637–642.

Liew, W.P.P., Mohd-Redzwan, S., 2018. Mycotoxin: its impact on gut health and microbiota. Front. Cell. Infect. Microbiol. 8 (FEB) https://doi.org/10.3389/fcimb.2018.00060.

Lu, M., Chen, C., Lan, Y., Xiao, J., Li, R., Huang, J., et al., 2020. Capsaicin - the major bioactive ingredient of chili peppers: bio-efficacy and delivery systems. Food Funct. 11 (4), 2848–2860. https://doi.org/10.1039/d0fo00351d.

Macdonald, S., Castle, L., 1996. A UK retail survey of aflatoxins in herbs and spices and their fate during cooking. Food Addit. Contam. 13 (1), 121–128. https://doi.org/10.1080/02652039609374387.

Mandeel, Q.A., 2005. Fungal contamination of some imported spices. Mycopathologia 159, 291–298. https://doi.org/10.1007/s11046-004-5496-z.

Olatunji, T.L., Afolayan, A.J., 2018. The suitability of chili pepper (Capsicum annuum L.) for alleviating human micronutrient dietary deficiencies: a review. Food Sci. Nutr. 6 (8), 2239–2251. https://doi.org/10.1002/fsn3.790.

Onyenekwe, P.C., Ogbadu, G.H., 1995. Radiation sterilization of red chili pepper (*Capsicum frutescens*). J. Food Biochem. 19 (1), 121–137.

Paterson, R.R.M., 2007. Aflatoxins contamination in chilli samples from Pakistan. Food Control 18 (7), 817–820. https://doi.org/10.1016/j.foodcont.2006.04.005.

Patriarca, A., Pinto, V.F., 2017. Prevalence of mycotoxins in foods and decontamination. Curr. Opin. Food Sci. 14 (1), 50–60. https://doi.org/10.1016/j.cofs.2017.01.011.

Paul, B., Singh, S.P., 2013. A review of solar dryers designed & developed for chilli. International Journal of Research in Advent Technology 1 (4), 62–72.

Peter, K.V., Indira, P., Mini, C., 2003. The cultivation and processing of Capsicum in India. In: Amit, Krishna De (Ed.), Capsicum the Genus Capsicum. Taylor & Francis, New York, pp. 139–143.

Prakash, V., Eipeson, W., 2003. Pose-harvest handling and processing of Capsicums. In: De, A.K. (Ed.), Capsicum the Genus Capsicum. Taylor & Francis, New York, pp. 163–175.

Prelle, A., Spadaro, D., Denca, A., Garibaldi, A., Gullino, M.L., 2013. Comparison of clean-up methods for ochratoxin a on wine, beer, roasted coffee and chili commercialized in Italy. Toxins 5 (10), 1827–1844. https://doi.org/10.3390/toxins5101827.

Prelle, A., Spadaro, D., Garibaldi, A., Gullino, M.L., 2014. Co-occurrence of aflatoxins and ochratoxin A in spices commercialized in Italy. Food Control 39 (1), 192–197. https://doi.org/10.1016/j.foodcont.2013.11.013.

Pruthi, J., 2003. Advances in post-harvest processing technologies of Capsicam. In: Amit, krishna De (Ed.), Capsicum the Genus Capsicum. Taylor &Francis, New York, pp. 175–213.

Pruthi, J.S., 2003. Chemistry and quality control of capsicum and capsicum products. In: Amit, Krishna De (Ed.), Capsicum the Genus Capsicum, pp. 25–70 (New York).

Ravi Kiran, D., Narayana, K.J.P., Vijayalakshmi, M., 2005. Aflatoxin B1 production in chillies (*Capsicum annuum* L.) kept in cold stores. Afr. J. Biotechnol. 4 (8), 791–795. https://doi.org/10.4314/ajb.v4i8.15183.

Sahar, N., Yousaf, S., Shibli, S., Khurshid, S., Iqbal, H.M., Akbar, Q.-U.-A., Arif, S., 2017. The impact of sun drying on the occurrence of aflatoxin in red chilies. J. Basic Appl. Sci. 13 (December), 632–637. https://doi.org/10.6000/1927-5129.2017.13.102.

Sendrowicz, T., Dubelaar, W., 2020. Business opportunity report: spices sector in Ethiopia. Report of Advanced Consulting 36. https://www.advanceconsulting.nl/assets/Uploads/spicesbor-ethiopia.pdf.

Set, E., Erkmen, O., 2014. Occurrence of aflatoxins in ground red chili pepper and pistachio nut. Int. J. Food Prop. 17 (10), 2322–2331. https://doi.org/10.1080/10942912.2013.800985.

Shamsuddin, Z.A., Khan, M.A., Khan, B.A., Ahmad, M.A., Ahmed, A., 1995. Contamination of red chilli with aflatoxin B 1 in Pakistan. Mycotoxin Res. 11 (1), 21–24. https://doi.org/10.1007/BF03192058.

Shimelis, T., 2021. Spices production and marketing in Ethiopia: a review. Cogent Food Agric. 7 (1), 1915558 https://doi.org/10.1080/23311932.2021.1915558.

Shirkole, S.S., Sutar, P.P., 2018. Modeling sorption phenomena and moisture migration rates in paprika (*Capsicum annuum* L.) using physicochemical characteristics. J. Food Sci. Technol. 55 (2), 678–688. https://doi.org/10.1007/s13197-017-2977-x.

Shumeta, Z., 2012a. Hot pepper production and MArketing in Southwest Ethiopia: an Alternative Enterprise for small scale farmers. Trends in Agricultural Economics 5 (3), 83–95.

Shumeta, Z., 2012b. Hot pepper production and marketing in southwest Ethiopia: an alternative enterprise for small scale farmers. Trends in Agricultural Economics. https://doi.org/10.3923/tae.2012.83.95.

Singh, P., Cotty, P.J., 2017. Aflatoxin contamination of dried red chilies: contrasts between the United States and Nigeria, two markets differing in regulation enforcement. Food Control 80, 374–379. https://doi.org/10.1016/j.foodcont.2017.05.014.

Srinivasan, K., 2016. Biological activities of red pepper (capsicum annuum) and its pungent principle capsaicin: a review. Crit. Rev. Food Sci. Nutr. 56 (9), 1488–1500. https://doi.org/10.1080/10408398.2013.772090.

Swamy, G.S.V.S., Wesley, B.J., 2017. Bio-efficacy of some botanicals as grain protectants against Callosobruchus maculatus (F.) infesting stored blackgram. Ind. J. of Eco. 44 (6), 663–666.

Tadesse, A., 2009. Increasing crop production T hrough improved plant protection. In: Tadesse, A., Plant (Eds.), Addis Ababa, Ethiopia: Plant Protection Society of Ethiopia.

Tesfa, T., Bayu, W., Gashaw, A., Beshir, H., Box, P.O., 2017. Spice production, marketing, and utilization in South wollo, Ethiopia. East African Journal of Sciences 11 (1), 27–36. https://doi.org/10.20372/nadre:1547201218.31.

Tesheshigo, M., Yimenu, K., Workineh, M., 2019. Evaluation of hot pepper varieties (*Capsicum species*) for yield related traits, quality and yield in burie district, West Gojjam zone, Ethiopia. International Journal of Plant Breeding and Crop Science 6 (3), 581–588.

Tsehaynesh, T., Abdi, M., Hassen, S., Taye, W., 2021. Aspergillus species and aflatoxin contamination in pepper (capsicum annuum L.) in West Gojjam, Ethiopia. Afr. J. Food Nutr. Sci. 21 (1), 17178–17194. https://doi.org/10.18697/ajfand.96.18815.

Tsuchiya, Y., Terao, M., Okano, K., Nakamura, K., Oyama, M., Ikegami, K., Yamamoto, M., 2011. Mutagenicity and mutagens of the red chili pepper as gallbladder cancer risk factor in Chilean women. Asian Pac. J. Cancer Prev. APJCP 12 (2), 471–476.

Udomkun, P., Wossen, T., Nabahungu, N.L., Mutegi, C., Vanlauwe, B., Bandyopadhyay, R., 2018. Incidence and farmers' knowledge of aflatoxin contamination and control in Eastern Democratic Republic of Congo. Food Sci. Nutr. 6 (6), 1607–1620. https://doi.org/10.1002/fsn3.735.

Yanti, L., Novalinda, D., Hernita, D., 2018. The processing Technology to improve the quality of chili in jambi province. In: Proceeding the International Seminar on Tropical Horticulture Horticulture for the Quality of Life. Bogor, pp. 232–238.

Yilmaz, R.K., 2017. The contamination rate of aflatoxins. In: Ground Red Peppers , Dried Figs , Walnuts without Shell and Seedless Black Raisins Commercialized, vol. 29, pp. 591–598. In Sakarya City Center.

Yogeesbh, H., Gowda, R., 2003. The storage of Capsicum. In: Capsicum the Genus Capsicum. Taylor & Francis, New York, pp. 214–222.

Yogendrarajah, P., Jacxsens, L., Saeger, S. De, De, B., 2014. Co-occurrence of multiple mycotoxins in dry chilli (Capsicum annum L.) samples from the markets of Sri Lanka and Belgium. Food Control 46 (1), 26–34. https://doi.org/10.1016/j.foodcont.2014.04.043.