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Sorghum Conservation Techniques in Three Agro-Climatic Zones and Their Impact on Food Security in Burkina Faso

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Abstract

The objective of this study was to examine the sorghum preservation techniques in response to climate variability and to evaluate the prevalence of aflatoxin B1 in selected sorghum stocks in Burkina Faso. The cross-sectional study was conducted over a period of six months, from October 2020 to January 2021. A questionnaire was administered to 450 sorghum farmers in order to ascertain their knowledge and practices with regard to conservation techniques. A total of 23 farmers' stocks were sampled for the determination of aflatoxin B1 using the Enzyme-Linked Immunosorbent Assay (ELISA) method and for the assessment of moisture levels using the Association of Official Agricultural Chemists (AOAC) method. A total of five distinct preservation techniques were identified. The most frequently utilized techniques were straw loft (49.2%) as a storage structure, pallets (36.69%) as the structure's internal management, plastic bags (40.42%) as packaging material, panicles (64.3%) as a form of storage, and chemical products (15.22%) as preservatives. Three biotic constraints were identified: insect (51.18%), rodent (30.14%), and mold (15.38%). Three significant abiotic constraints were identified: humidity (44.6%), lack of hygiene (15.2%), and grain immaturity (10.2%). A comparative analysis reveals that the majority of these techniques and constraints exhibit notable differences between climatic zones, largely due to the influence of climatic variability. The aflatoxin B1 level exhibited considerable variation, ranging from 0 µg/kg to 2.07 ± 0.08 µg/kg DM. Of the analyzed stocks, 38% were found to be contaminated. Abiotic and biotic factors exert influence on sorghum stocks. Chemical agents are employed for their protection, and contamination by aflatoxin B1 is a further issue. However, the levels of contamination observed are not cause for concern.

Keywords

Climate, Storage, Sorghum, Aflatoxin B1, Burkina Faso

1. Introduction

Sorghum plays an important role in the diets of people in developing countries. It is a cereal of global importance, employed in both domestic and industrial contexts [1]. In West Africa, sorghum is utilized as a household foodstuff in the form of pasta and infant flour, and in industry as malt for the production of beer and other types of alcohol [2].

Due to its resilience to climate change, sorghum has been the subject of numerous studies, particularly those pertaining to genetic improvement, varietal selection for increased yields, and the physical and nutritional characteristics of the crop [3] [4]. These studies collectively reinforce the importance of sorghum as a vital crop in the effort to combat food and nutrition insecurity [5].

The climate of Burkina Faso is characterized by two distinct seasons: a dry season and a rainy season. The country is traditionally divided into three agro-climatic zones: the Sahelian zone in the north, with an average annual rainfall of less than 600 mm; the northern Sudanian zone in the center, with an average annual rainfall of between 600 and 900 mm; and the southern Sudanian zone in the south, with an average annual rainfall of more than 900 mm. The rainy season lasts approximately six months [6]. The Sahelian zone is subdivided into two sub-zones: the strict Sahelian zone and the sub-Sahelian zone. A notable shift in climate patterns has been observed in recent years, characterised by an increase in extreme weather events such as floods and droughts, as well as a general decline in precipitation [6] [7]. These climatic changes have a considerable impact on cultivation and conservation practices and on production.

In Burkina Faso, sorghum is the second most important cereal crop after maize, with a production volume of 1,839,571 tons in 2020 [8]. Sorghum is an essentially rained cereal that is able to adapt to water stress. Furthermore, there are a number of different varieties, which has resulted in the cultivation of sorghum in all three of Burkina Faso's agro-climatic zones. The seasonal availability of sorghum and the potential for price fluctuations prompt actors in the field to store significant quantities for future use. It has been demonstrated that the nutritional value of cereals can be influenced by biotic and abiotic factors during the storage period [9]. Consequently, sorghum is susceptible to these effects. The traditional storage systems employed utilize granaries for the storage of sorghum in either grain or panicle form, with the utilization of natural plant substances for the protection of the stored grain [10]. In light of evolving agricultural practices, climate change, and the emergence of new pests, traditional conservation methods are no longer sufficient [11]. A number of studies have documented the presence of pests in sorghum stocks. Among these pests, insects, rodents, and molds have been identified as the most prevalent [10] [12]. Molds are purported to be accountable for approximately 25% of post-harvest cereal losses, a consequence of the toxins they produce [13] [14]. The ingestion of foodstuffs contaminated with aflatoxins endangers the health of humans and animals alike [15] [16].

Synthetic and natural chemicals are also employed for the purpose of stock protection. Furthermore, the proliferation of molds on stocks and the production of mycotoxins are enhanced by specific environmental conditions, including humidity, temperature and pH [17].

May correlation be exists between the agro-climatic zone and conservation technology, as well as between the agro-climatic zone and the presence of biotic and abiotic factors that contribute to stock alteration.

The objective of this study was twofold: firstly, to examine the sorghum preservation techniques in the context of climate variability; and secondly, to ascertain the prevalence of aflatoxin B1 in selected sorghum stocks in Burkina Faso.

2. Materials and Methods

2.1. Study Areas and Sites

The study was conducted between October 2020 and January 2021 across three agro-climatic zones in Burkina Faso. **Figure 1** shows the three climatic zones under consideration: the sub-Sahelian zone, the North Sudanese zone, and the South Sudanese zone. The study encompassed five administrative regions and nine municipalities distributed across the three climatic zones. The North-Central region of Burkina Faso represents the northernmost extent of the Sahelian zone, while the East-Central and Boucle du Mouhoun regions correspond to the North Sudanese zone. In contrast, the South-West and Hauts Bassins regions correspond to the South Sudanese zone (**Table 1**).

Table 1. Characteristics of study areas.

Climatic zones	Administrative regions	Communes	Villages
Sub-Sahelian 13˚05' North 1˚05' West	Center-north	Boussouma	Boussouma, Zikiema
		Korsimoro	Taonsin, Yimiougou
		Pissila	Lebda, Goema, and Forgui
North-Sudanese between 11˚30' and 14˚ latitude North	Center-East	Andemtenga	Simba, Andemtenga, Kougre
	Loop of the Mouhoun	Bondokuy	Kera, Tankuy
		Bourasso	Lekuy, Barakuy
South-Sudanese to the south of 11˚30' latitude North	High basins	Kourinion	Sidi, Dan
	Southwest	Loropeni	Lokosso, Loropeni
		Nako	Nako, Bakpara

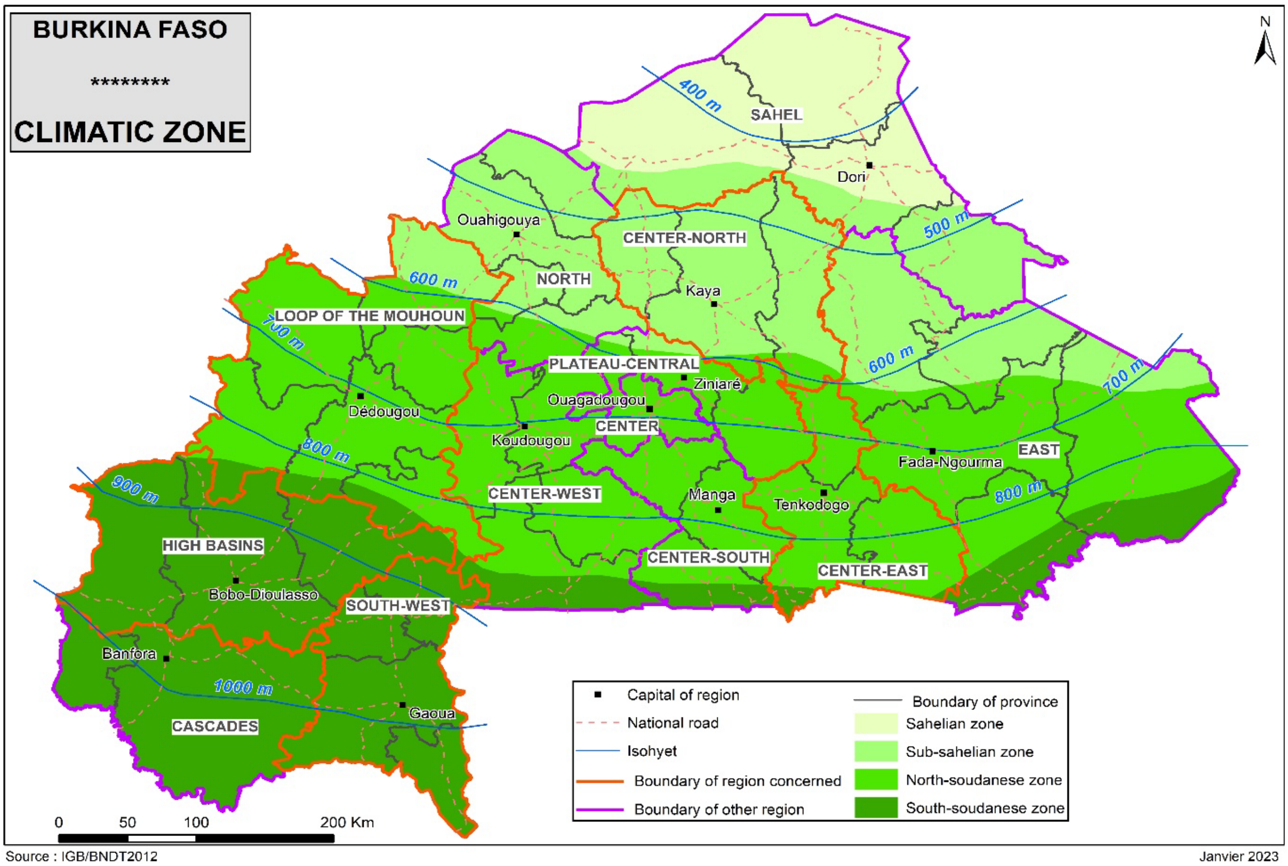

Figure 1. Locality of study areas.

2.2. The Type of Study

The study employed a cross-sectional design, enabling the collection of both qualitative and quantitative data. A questionnaire was administered to producers in order to ascertain their knowledge and practices regarding sorghum storage and conservation techniques. A number of sorghum samples were obtained for subsequent laboratory analysis.

2.3. Sampling and Data Collection

A sample was selected by randomly drawing from the list of producers. The sample size was calculated using the proportion of farmers (80%) as the probability of calculation [8]. This resulted in a minimum sample size of 250 farmers, in accordance with the methodology described by Swartz and subsequently adapted by Lwanga [18]. Three points were selected for sampling. Data were collected by administering a 70-item questionnaire to 450 sorghum farmers in nine communes in five regions of Burkina Faso. The regions included in the study were the Center-North, Center-East, Loop of Mouhoun, High Basins, and South-West. Following its design, the questionnaire was presented to the representatives of the producers in order to adapt it to the realities of the field. The questionnaire included questions on the type of storage used, the structure of the storage facility, internal management practices, the packaging material used, the use of preservatives, and the abiotic and biotic factors that impact the quality of the stock. It also covered the duration for which the stock is conserved. The mobile data collection software ODK Kobo Collection was installed on tablets and employed for the purpose of data collection. Following the completion of the household survey, 23 sorghum samples (150 g each) were collected in the sub-Sahelian zone for the determination of aflatoxin levels.

2.4. Determination of the Moisture Content

The moisture content of the samples was determined by mass difference after oven drying at 105˚C for 24 hours of 5 grams of homogenate sample, in accordance with the AOAC method [19].

2.4.1. Extraction of Aflatoxin B1

The samples received are recorded and pooled in batches of ten. Subsequently, the entire sample (100 g) is ground using a Kenstar sterling mill. In a mixer (Kenstar sterling grinder), 10 g of the previously weighed sample is introduced, and 50 mL of the extraction solution, composed of potassium chloride, methanol, and Chromasolv (30/70 v/v), is added. The entire mixture is then mixed for 30 seconds and subsequently filtered through No. 4 Wattman paper. The resulting filtrate (10 ml) is collected in a 10 ml graduated glass tube and stored in a refrigerator for subsequent analysis. The determination of aflatoxin B1 in the sample was conducted using an immunological method, specifically the enzyme-linked immunosorbent assay (ELISA), as described by Kumar *et al.* (2017) and Abbas *et al.* [20].

2.4.2. Determination and Quantification of AFTB1

A volume of 150 µL of the AFB1-BSA conjugate solution (150 ng/mL) was introduced into each well of the ELISA plate, incubated in a Heidolph Titramax 1000 incubator at 37˚C for one hour, and washed three times with PBS-Tween. To each well, 150 µL of 0.2% BSA prepared in PBS-Tween was added, incubated at 37˚C for 1 hour, and washed three times with PBS-Tween. A volume of 50 µL of the antiserum dilution was added to each standard dilution (100 µL) and to each well containing the test sample (100 µL). The mixture was incubated for one hour at 37˚C to facilitate the reaction between the toxin present in the sample and the antibody. Following this, the plate was washed three times with PBS-Tween. A volume of 150 µL of alkaline phosphatase-labelled anti-rabbit IgG was introduced into each hole of the plate, incubated for one hour at 37˚C, and then the plate was washed with PBS-Tween. The substrate solution (p-nitrophenyl phosphate) was then added and incubated at 37˚C for 30 minutes. A control sample was prepared under the same conditions using a healthy product extract. The plate was then inserted into a spectrophotometer (iMark TM Microplate Reader BIO RAD) for OD reading at 450 nm. The resulting curve was plotted by taking the AFB1 concentrations on the x-axis and the optical density values on the y-axis, in accordance with the methodology described by Abbas *et al.* (2004).

2.5. Data Processing and Analysis

The data were transferred from the ODK Kobo collection software to Excel for subsequent analysis. The data were processed and analyzed using Excel 2013 and R.4.2.0 software. The diagrams were created using the Rcomander package and Excel 2013, while the multimodal logistic regression was performed using Rgui (64-bit). The calculation of means and standard deviations for moisture content and aflatoxin B1 content was conducted using the Microsoft Excel 2013 software.

3. Results

3.1. Sorghum Storage Techniques

The study of sorghum post-harvest practices in different agro-climatic zones enabled the identification of five preservation techniques (**Table 2**), namely the use of storage structures, the internal layout of these structures, the form of storage, the type of packaging, the use of preservatives, three groups of pests (insects, rodents, and molds), and four risk factors for mold infestation, such as humidity, lack of hygiene, the state of grain ripeness, and the late harvest.

These techniques were observed to be employed in a variety of storage contexts, and their effectiveness was evaluated in relation to the aforementioned risk factors.

Table 2. Sorghum storage techniques.

Sorghum Storage Techniques	Techniques details
Form of storage	Grains, panicles
Storage structure	Straw loft, banco loft, house, storehouse
Structure layout	Tarpaulins, chemical product, pallets, natural
Sorghum packaging	Plastic bag, other packaging (jute bag, double-bottom bag)
Use of a preservative	Chemicals product (phostoxin, rambo) and natural preservatives (neem leaves, basil, ash)
Biotic alteration factors	Insect, Rodents, and Molds
Abiotic alteration factors (linked with mold activity)	Humidity, lack of hygiene, immature grains, late harvest, other risk factors (air, insect action)

3.2. Forms of Storage

Sorghum is stored in two forms: panicle storage and grain storage subsequent to threshing (**Figure 2**). There is a notable variation in the rate of utilization across different agro-climatic zones ($P < 0.05$). The storage of grains is employed by 50% of producers in the Northern Sudanese zone, 9.9% in the Sub-Sahelian zone, and 40.1% in the Southern Sudanese zone. The storage of sorghum in the form of panicles is practiced by 58% of producers in the Sub-Sahelian zone, 32.1% in the Northern Sudanese zone, and 9.9% in the Southern Sudanese zone.

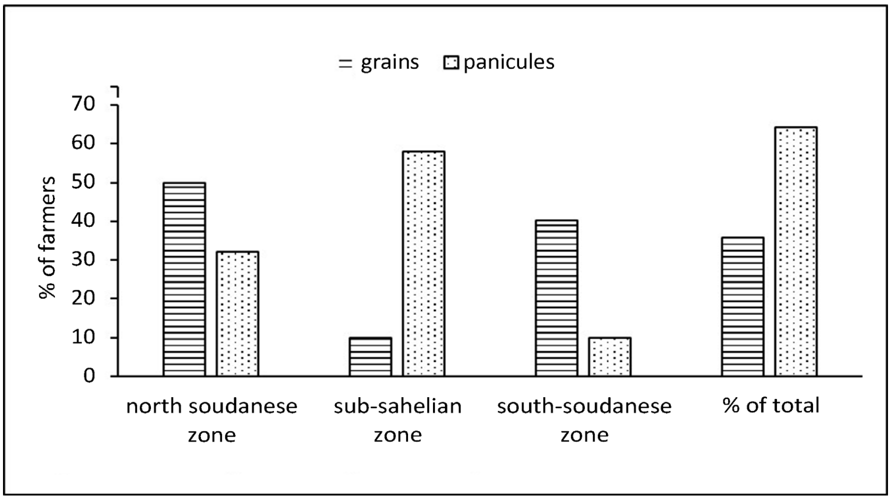

Figure 2. Form of sorghum storage according to climatic zones.

3.3. Sorghum Storage Structures

The primary structures utilized for sorghum storage are the straw loft, house, banco loft, and storehouse (Figure 3). The utilization of storage structures exhibits notable variability across different agro-climatic zones ($P < 0.05$). The results demonstrate that the straw loft is the predominant storage structure employed in the Sub-Sahelian zone (72.6%), followed by the North Sudanese zone (26.4%), with 0.9% of producers utilizing the straw loft in the South Sudanese zone. The use of the banco loft also exhibits regional variation, with 51.2%, 46.5%, and 2.3% of producers in the South Sudanese, North Sudanese, and Sub-Sahelian zones, respectively. Furthermore, the house is utilized as a sorghum storage structure by 48.3%, 38.1%, and 13.6% of producers in the Northern Sudanese, South Sudanese, and Sub-Sahelian zones, respectively. Additionally, the warehouse is employed by 60.3%, 32.8%, and 6.9% of sorghum producers in the Northern, Southern, and Sub-Sahelian zones, respectively.

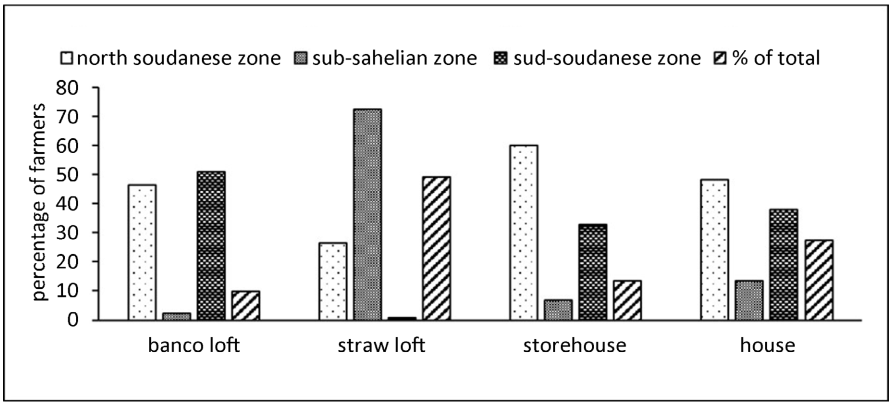

Figure 3. Sorghum storage structures according to climatic zones in percentage.

3.4. Internal Management of Sorghum Storage Structures

Prior to storage, producers undertake the necessary interior arrangements of the storage structure. The tools typically employed in this process include tarpaulins, chemicals, natural products, and pallets. It is notable that the specific tools and techniques employed may vary considerably across different agro-climatic zones (Table 3). Pallets are utilized by 50.6%, 32.3%, and 17.1% of producers in the Northern, Southern, and Sub-Sahelian zones, respectively. Natural substances, including neem leaves and ash, are employed by 58.8%, 23.5%, and 17.6% of producers in the Northern zones. In the Southern and Sub-Sahelian zones, respectively; chemicals are used by 53%, 44%, and 3% of producers for internal management in the Sub-Sahelian, North Sudanese, and South Sudanese zones, respectively; tarpaulins are used by 44.4%, 33.3%, and 22 In the South Sudanese, North Sudanese, and Sub-Sahelian zones, respectively, 0.2% of producers do not engage in any internal management practices. The proportions of these producers are 57.3%, 26.1%, and 17.1% in the Sub-Sahelian, Northern Sudanese, and Southern Sudanese zones, respectively.

Table 3. Techniques for the internal management of the sorghum storage structure.

Agroclimatic Zones	Tarpaulins N (%)	Chemical N (%)	Natural N (%)	Pallets N (%)	No management N (%)
North Soudanese Zone	3 (33.3)	44 (44)	10 (58.8)	83 (50.6)	41 (26.1)
Sub-Sahelian Zone	2 (22.2)	53 (53)	3 (17.7)	28 (17.1)	90 (57.3)
South-Soudanese Zone	4 (44.5)	3 (3)	4 (23.5)	53 (32.3)	26 (16.6)
Total	9 (100)	100 (100)	17 (100)	164 (100)	157 (100)

N represents the number of producer's responses; (%) represents the percentage of producers.

3.5. Sorghum Packaging

Plastic bags are the most commonly used packaging material in external, unpackaged storage (Table 4). In the Sub-Sahelian, North Sudanese, and South Sudanese zones, sorghum is stored in facilities without any conditioning. The percentages of producers in these zones who store sorghum in this way are 51.3%, 38.7%, and 10%, respectively. The most prevalent packaging material employed by producers in the North Sudanese, South Sudanese, and Sub-Sahelian zones is plastic bags, utilized by 43.9%, 32.4%, and 23.7% of producers, respectively. The jute bag and the double-bottom bag (other) are employed by a relatively small proportion of producers, with 64%, 36% and 0% respectively in the Sub-Sahelian, South Sudanese and North Sudanese zones.

Table 4. Packaging material of sorghum.

Agro-Climatic Zones	No packaging N (%)	Plastic bag N (%)	Other packaging N (%)
North Sudanese Zone	89 (38.7)	76 (43.9)	0 (0)
Sub-Sahelian Zone	118 (51.3)	41(23.7)	16 (64)
South Sudanese Zone	23 (10)	56 (32.4)	9 (36)
Total	230 (100)	173 (100)	25 (100)

3.6. Utilization of Preservatives in Sorghum Stocks

The most commonly utilized preservatives are chemical (phostoxin, rambo) and natural (neem leaves, basil, ash) (Table 5). The majority of producers in the Northern, Sub-Saharan, and Southern Sudanese zones (39.6%, 39.1%, and 21.3% respectively) utilize sorghum storage methods that do not involve the use of preservatives. The use of chemical products is prevalent, with 53.8%, 35.4%, and 10.8% of producers in the Sub-Saharan, Northern, and Southern Sudanese zones, respectively, utilizing them. The use of natural preservatives is observed in 43.8%, 31.2%, and 25% of producers in the Sub-Sahelian, Northern Sudanese, and Southern Sudanese zones, respectively. In the Southern Sudanese zone, 62.5% of producers employ other types of preservatives, while in the Northern Sudanese zone, 37.5% do so. In the Sub-Sahelian zone, however, no producers utilize such methods.

Table 5. Preservatives used in sorghum according to the climatic zones.

Agroclimatic Zones	Chemical N (%)	Natural N (%)	No preservative N (%)	Other preservatives N (%)
North Sudanese Zone	23 (35.4)	5 (31.2)	134 (39.6)	3 (37.5)
Sub-Sahelian Zone	35 (53.8)	7 (43.8)	132 (39.1)	0 (0)
South Sudanese Zone	7 (10.8)	4 (25)	72 (21.3)	5 (62.5)
Total	65 (100)	16 (100)	338 (100)	8 (100)

3.7. Biotic and Abiotic Factors Affecting Sorghum Stocks

3.7.1. Biotic Factors Affecting Sorghum Stocks (Enemies)

The following three main groups of living beings were identified as having the potential to alter stocks: insects, rodents, and molds (Table 6). It should be noted that the presence of these enemies varies from one area to another. The presence of insects was mentioned by producers in different ways depending on the zone in question, with figures of 45.4%, 35.9%, and 19.7% for the North Sudanese, Sub-Sahelian, and South Sudanese zones, respectively. Molds were observed by 44.9%, 28.6%, and 26.5% of producers, respectively, in the Sub-Sahelian, Southern, and Northern Sudanese zones. Rodents were identified by 49%, 44.3%, and 6.7% of producers, respectively, in the Northern, Sub-Sahelian, and Southern Sudanese zones. Some producers indicated the presence of additional enemies, including birds and animals, in the Sub-Sahelian zone (82.4%) and the Northern Sudanese zone (17.6%). Conversely, other producers asserted the absence of such enemies in the Southern Sudanese zone (100%).

Table 6. Enemies of sorghum stocks (biotic factors).

Agro-Climatic Zones	Insect N (%)	Rodent N (%)	Mould N (%)	No enemies N (%)	Other enemies N (%)
North Sudanese Zone	148 (45.4)	94 (49)	26 (26.5)	0 (0)	3 (17.6)
Sub-Sahelian Zone	117 (35.9)	85 (44.2)	44 (44.9)	0 (0)	14 (82.4)
South Sudanese Zone	61 (18.7)	13 (6.8)	28 (28.6)	4 (100)	0 (0)
Total	326 (100)	192 (100)	98 (100)	4 (100)	17 (100)

3.7.2. Abiotic Factors Favoring Mold Development in Sorghum

A total of five factors were identified as favoring the development of mold in sorghum. The aforementioned factors were identified as humidity, lack of hygiene, late harvest, immature grains, and other types of factors (air, insect action) (Figure 4). The primary risk factor was moisture, accounting for 52% of the total, followed by lack of hygiene (18%), immature grains (12%), late harvest (8%), and other risks (10%). The moisture levels are 47.3%, 27.9%, and 24.8% in the Sub-Sahelian, Northern-Sudanese, and Southern-Sudanese zones, respectively. The prevalence of inadequate hygiene practices was found to be 44%, 28.6%, and 27.5% in the Sub-Sahelian, Northern-Sudanese, and Southern-Sudanese zones, respectively. The proportion of immature grains is 47.5%, 39%, and 13.6% in the Sub-Sahelian, Northern-Sudanese, and Southern-Sudanese zones, respectively. Additionally, other types of risk were identified, with respective levels of 54.6%, 41.5%, and 3.8% in the Southern Sudanese, Sub-Sahelian, and Northern Sudanese zones. The Sub-Sahelian zone is characterized by the highest levels of risk factors.

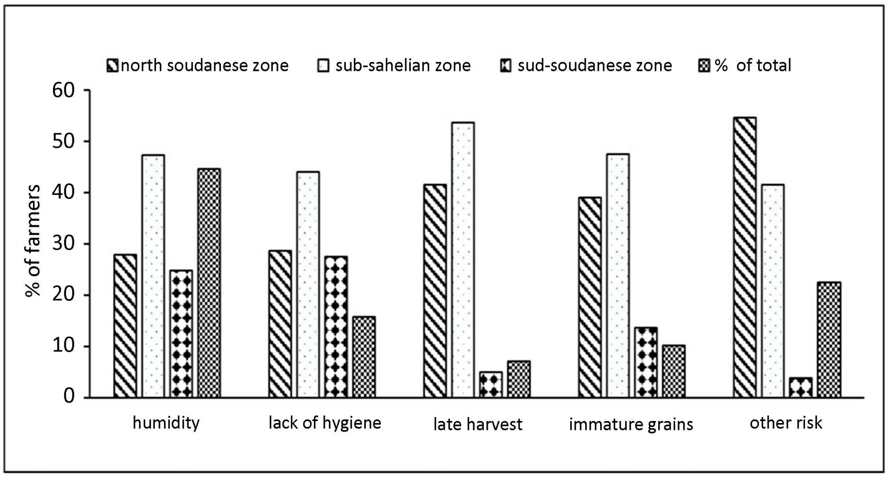

Figure 4. Risk of mold proliferation factors according to climatic zones in percentage.

3.8. Linked between Climate Zones and Storage Technology

Table 7 presents the results of a general linear regression analysis investigating the impact of agro-climatic zones on sorghum conservation techniques and storage constraints.

There is a relationship between the use of preservatives, structural management, sorghum packaging, storage structures, and risk factors; however, there is no correlation between enemies and climatic zones.

Table 7. General linear regression analysis of the impact of agro-climatic zones on sorghum conservation techniques and storage constraints.

Coefficients	Odds ratios	Estimate	Std. Error	Z value	Pr(>|z|)
Conservatives Use	2.05e−01	−1.58	0.95	−1.67	0.110.
Sub-Sahelian Zone	3.56e+00	1.27	0.38532	3.28	0.001***

Continued

South Sudanese Zone	8.13e−01	−0.21	0.37903	−0.55	0.584
Structure Management	3.6e+01	3.60	0.8255	4.36	1.33e−04***
Sub-Sahelian Zone	5.02e−01	−0.69	0.32	−2.17	0.030*
South Sudanese Zone	2.79e−01	−1.28	0.40	−3.16	0.002**
Sorghum Packaging	1.52e−01	−1.89	1.63	−1.15	0.249
Sub-Sahelian Zone	6.43e+01	4.16	1.16	3.60	3.19e−04***
South Sudanese Zone	1.02e+02	4.63	1.28	3.61	3.09e−04***
Sorghum Storage Form	2.18e+10	23.80	4298.86	0.01	0.996
Sub-Sahelian Zone	1.60e+00	0.47	1.06	0.45	0.656
South Sudanese Zone	5.14e−01	−0.67	1.13	−0.59	0.557
Storage Structure	8.37e+08	20.55	2759.77	0.01	0.994
Sub-Sahelian Zone	1.57e+01	2.75	1.08	2.54	0.011*
South Sudanese Zone	2.44e−02	−3.71	0.92	−4.02	5.73e−05***
Factor of Risk	5.16e−04	−7.57	1.98	−3.83	1.30e−04***
Sub-Sahelian Zone	2.31e+01	3.14	0.43	7.26	3.89e−13***
South Sudanese Zone	4.03e+01	3.70	0.83	4.48	7.61e−06***
Sorghum Enemies	5.14e+17	40.78	2.49e+05	0.00	1.000
Sub-Sahelian Zone	6.42e−10	−21.17	1.21e+05	0.00	1.000
South Sudanese Zone	5.05e−27	−60.55	24315.21	−0.002	0.998

The following codes are used to indicate the level of statistical significance: A three-star rating (***) indicates that the P-value is statistically significant at the 0.001 level. A two-star rating (**) denotes a statistically significant P-value at the 0.01 level. A one-star rating (*) represents a statistically significant P-value at the 0.05 level. A full stop (.) indicates a statistically significant P-value at the 0.1 level. Finally, a point (.) denotes a statistically significant P-value at the 10% level. The term "IC" refers to the interval of confidence.

3.9. Aflatoxin B1 and Moisture Content of Sorghum

Table 8 presents the results of the analysis of aflatoxin B1 and moisture content in sorghum stocks, along with details of the packaging material and storage structure.

Of the 23 samples subjected to analysis, eight were found to be contaminated with aflatoxins B1, representing a contamination rate of 34.78%. The aflatoxin B1 content exhibited a range of 0 to 2.07 ± 0.08 μg/kg, while the moisture content spanned 5.16 ± 0.13 to 7.49 ± 0 g/100 g. The highest aflatoxin concentration was observed in sorghum stored in a residential setting as grain in a plastic bag.

Table 8. Aflatoxin B1 and humidity levels in sorghum according to storage structures and packaging in the sub-Sahelian zone of Burkina Faso.

Localities	Storage structures	Materiel of the packaging	Moisture (g/100 g MS)	AFT B1 levels (µg/kg MS)
Zikiema	Straw loft	No packaging	5.35 ± 0.01	0.37 ± 0.07
Zikiema	House	Plastic bag	6.97 ± 0.02	0.00 ± 0
Zikiema	House	Plastic bag	6.82 ± 0	0.38 ± 0.53
Zikiema	House	Plastic bag	6.36 ± 0.04	1.33 ± 0.08
Zikiema	House	Plastic bag	6.90 ± 0.12	0.00 ± 0
Forgui	Straw loft	No packaging	5.54 ± 0.15	0.00 ± 0
Forgui	House	Plastic bag	5.94 ± 0.20	2.07 ± 0.08
Forgui	House	Plastic bag	6.13 ± 0.03	0.00 ± 0
Forgui	Straw loft	No packaging	5.16 ± 0.13	0.26 ± 0.22
Lebda	Straw loft	No packaging	5.37 ± 0.09	0.26 ± 0.07
Korsimoro	Straw loft	No packaging	5.33 ± 0.09	0.00 ± 0
Boussouma	Storehouse	Plastic bag	5.95 ± 0.07	0.00 ± 0
Korsimoro	Straw loft	No packaging	5.32 ± 0.04	0.37 ± 0.07
Korsimoro	House	Plastic bag	5.34 ± 0.01	0.00 ± 0
Korsimoro	Straw loft	No packaging	5.41 ± 0.09	0.21 ± 0
Boussouma	House	Plastic bag	7.49 ± 0	0.00 ± 0
Boussouma	Banco loft	No packaging	6.25 ± 0.01	0.00 ± 0
Forgui	House	Plastic bag	6.75 ± 0.01	0.00 ± 0
Forgui	Storehouse	Plastic bag	6.23 ± 0.05	0.00 ± 0
Forgui	Straw loft	No packaging	5.40 ± 0.04	0.00 ± 0
Lebda	House	No packaging	5.45 ± 0.54	0.00 ± 0
Zikiema	Straw loft	No packaging	7.25 ± 0.14	0.00 ± 0
Zikiema	House	Plastic bag	6.18 ± 0.09	0.00 ± 0

4. Discussion

Sorghum storage technologies based on agro-climatic zones

The five techniques identified are present within the climatic zones of Burkina Faso, though their utilization varies according to the specific climatic zone in question. Two challenges encountered by producers during the storage phase were identified: the risk of pest attack and the potential for contamination of sorghum by molds, which may result in the production of aflatoxins.

In the sub-Sahelian and northern Sudanese zones, sorghum is stored primarily in the form of panicles, whereas in the southern Sudanese zone, it is stored as grains. A 2020 study found that 75% of farmers in Senegal stored sorghum as grains [21], which corroborates the findings from the southern Sudanese zone. The results of the linear logistic regression indicate that the observed difference in storage form is not attributable to climate variability, but may be associated with the type of storage structure employed.

In the sub-Sahelian zone, the straw loft is the most prevalent sorghum storage structure. In the northern Sudanese zone, the dwelling house and the storehouse are the most commonly used sorghum storage structures. In the southern Sudanese zone, the banco loft is the most frequently utilized sorghum storage structure. This result corroborates that found by Waongo in 2013, who identified the granary as the most commonly used storage structure in a study conducted in the South Sudanese zone of Burkina Faso [10]. The linear regression analysis suggests that climate variability is a key factor influencing the choice of storage structure (**Table 7**). The use of the storehouse, the straw loft, and the dwelling house is observed to be relatively infrequent in the Southern Sudanese zone (OR = 2.443111e-02; $P < 0.001$). Conversely, the straw loft is a highly prevalent storage structure in the sub-Sahelian zone (OR = 1.565440e+01; $P < 0.05$).

Prior to storage, sorghum is packed in plastic bags or other materials or stored directly without any packaging in the storage structure. These techniques also vary from one zone to another. The observed variation in the forms of packaging can be explained by the difference in climatic zones. The use of plastic bags is low in the sub-Sahelian zone, where sorghum is generally stored in straw barns with panicles without packaging (OR = 6.434996e+01; $P = 0.000319$). In contrast, it is most commonly used in the South Sudanese zone (OR = 1.021459e+02; $P = 0.000309$).

The internal management of storage structures exhibits considerable variation across different zones. Four main approaches are observed: the use of pallets, synthetic chemical pesticides and fungicides, natural substances (such as neem leaf, basil, ash), and tarpaulins. The majority of producers who do not implement any management strategies and those who utilize chemical products for storage structure management are located in the sub-Sahelian zone (OR = 5.020835e-01; $P = 0.030106$). In the northern Sudanese zone, the majority of respondents indicated that they use pallets or natural substances. In the Southern Sudanese zone, the most commonly used material is tarpaulins (OR = 2.785807e-01; $P = 0.001591$). The utilization of synthetic chemicals for the internal environment of storage structures may serve as a method of pest control within storage facilities. The linear logistic regression model indicates that the management of structures is influenced by climatic zones.

It has been demonstrated that certain plant substances can be employed to control pests while simultaneously ensuring the continued wellbeing of consumers. Furthermore, these studies have addressed the utilization of synthetic chemicals for the safeguarding of sorghum stocks, while underscoring the potential risks to public health [22] [23]. This method has the potential to readily result in the product coming into contact with sorghum grains, which could subsequently lead to adverse health effects. The practice of storing without any preservatives exhibits minimal variation between the Northern Sudanese zone (40%) and the Sub-Sahelian zone (39%); it is markedly different in the southern Sudanese zone (21%). The utilization of chemical and natural substances for the purpose of preservation exhibits a degree of variation between different zones, with a notable increase in the prevalence of chemical substances observed in the sub-Sahelian zone. The use of chemicals in the sub-Sahelian zone may be attributed to the specific climatic conditions prevailing in this region (OR = 3.561945e+00; P = 0.000978). The low use of natural preservatives is partly due to the increasing use of chemicals, which is a result that is consistent with those found by other authors [10] [23] [24]. Savadogo was also reported that the preference for chemical substances over natural preservatives can also be attributed to the growing resistance of pests to natural products and the potential influence of accessibility and cost [22].

Enemies of sorghum stocks

The principal enemies of sorghum stocks are insects, rodents and molds. The prevalence of these pests in stocks varies according to the specific agro-climatic zone in question. In the Northern Sudanese zone, insects and rodents represent the most prevalent pests of sorghum stocks, while molds are the predominant culprits in the sub-Sahelian zone. These variations can be attributed to the types of conservation techniques employed, particularly the use of pesticides, packaging, and the type of storage structure, which are not directly influenced by climatic variability. These findings align with those of other researchers who have identified insects as the primary culprits behind the deterioration of cereal stocks [10] [25] [26]. It has been demonstrated that insects perforate the grains, consume a portion of the albumen, and contaminate them. The resulting openings serve as entry points for molds, which metabolize the nutrients in the grain by producing toxins [27].

Risk factors for mold attack and aflatoxin contamination

The primary factors contributing to the proliferation of molds in sorghum stocks, as identified by producers, are moisture, lack of hygiene and the immaturity of grains. The perception of these factors varies significantly depending on the climatic zone in question. It would appear that the agro-climatic zone in which a given crop is cultivated has a strong influence on the level of risk associated with these factors. This can be explained by the extensive use of straw barns, which are structures constructed from local materials that are not particularly resistant to climatic hazards. In the Southern Sudanese zone, the factors that facilitate the development of molds in stocks are the presence of humidity, a lack of hygiene ($P < 0.01$) and the immaturity of the sorghum grains (OR = 4.032144e+01; P = 7.61e-06). This can be attributed to the elevated precipitation levels in the region, the storage of grains in residential structures, the early harvesting of crops, or the premature conclusion of the rainy season. Fall (2020) demonstrated that inadequate grain storage techniques are a primary cause of mold contamination of stocks [21], which aligns with our findings. It has been demonstrated that elevated humidity, inadequate hygiene, and insect activity are the primary factors that facilitate mold growth during storage and aflatoxin production [28] [29].

Sanitary quality of the sorghum stocks

Mycotoxins are increasingly implicated in foodborne illness and growth retardation in children, and are postulated to be a cause of diseases such as cancer [30]. Aflatoxin B1 is the most prevalent and the most deleterious to human health; it has the potential to contaminate crops at any stage of the supply chain, from farm to storage [31]. Prolonged exposure to aflatoxins has been linked to an increased risk of developing liver cancer [32] [33]. Of the 23 sorghum samples subjected to analysis, eight were found to be contaminated with aflatoxin B1, representing a contamination rate of 34.78%. The mean concentration is 0.66 μg/kg. Only one stock (4.35%) exhibited a concentration exceeding the European standard for aflatoxin B1 in raw materials [34]. It can therefore be concluded that the majority of the samples are of satisfactory quality in terms of their aflatoxin B1 content. A study conducted by the European Food Safety Authority (EFSA) in 2007 revealed that cereals other than maize exhibited lower levels of contamination by aflatoxin B1 (7%), with an average content of 0.35 μg/kg. In comparison, our study identified a contamination rate of 34.78% and an average content of 0.66 μg/kg, which exceeded the levels documented by the EFSA [35]. In a study conducted in 2009, Rocha and colleagues observed a 10.5% AFB1 contamination rate in freshly harvested maize. Contamination levels higher than those observed in the present study have been reported by Trevino (2016) on sorghum (40%) and Ratnavathi (2016) on sorghum harvested during the rainy season [36] [37]. In a study conducted by Kortei *et al.*, a higher rate of contamination was observed, with AFTB1 concentrations ranging from 0.66 ± 0.06 to 5.51 ± 0.26 μg/kg [38]. Additionally, Leiva reported the highest level of AFB1 contamination in animal feed at 14,927.61 μg/kg [39]. The AFB1 levels identified in our stocks are lower than those reported by Udomkun [12]. The discrepancies in contamination rates and aflatoxin concentrations may be attributed to the fact that the majority of contamination occurs during the storage period, climatic variability, and the utilization of disparate preservation techniques and technological treatments in the case of flours. Furthermore, the utilization of preservatives in stocks may impede the synthesis of aflatoxins. This has been evidenced by Sultana through the employment of neem leaves (Azadirachta indica) to preserve maize, rice, and wheat [40]. Furthermore, studies have indicated the occurrence of pre-harvest contamination of cereals with aflatoxins [41]. Nevertheless, these levels remain below the maximum threshold set by the European Commission (EC), which is 2 μg/kg. The risk factors for *Aspergillus* and aflatoxin contamination of cereals include moisture content exceeding 10% and prolonged storage periods [42]. The low levels of aflatoxin B1 found in the sorghum samples can thus be attributed to their low moisture content, which was below 10%.

5. Conclusion

The findings of this study have enabled the identification of sorghum conservation techniques according to climatic variability, as perceived by producers. The interaction analysis was conducted with regard to the North Sudanese zone, which represents an intermediate zone between the Sub-Sahelian and South Sudanese zones. This study identified five conservation techniques and two conservation-related problems. The straw loft is the most prevalent storage structure. Sorghum is typically stored in panicles. The product is stored without any internal management or packaging, either in straw lofts or in structures fitted with chemicals and packaged in plastic bags. It is common practice to introduce chemical preservatives into the product. The primary factors conducive to the proliferation of molds and the production of aflatoxins are humidity and a lack of hygiene. It would appear that these sorghum preservation techniques vary from one agro-climatic zone to another, and that this variation represents an adaptation to climatic variability. An analysis of aflatoxins in some stocks in the sub-Saharan zone revealed that 38% of the stocks were contaminated, yet the majority of aflatoxins B1 contents were below the maximum tolerable standards set by the European Commission for cereal grains (2 μg/kg). The utilization of these diverse techniques serves to enhance resilience to climatic fluctuations and pest infestation. In light of the above, we intend to extend the study to encompass the three agro-climatic zones, with a view to assessing aflatoxin content in grain stocks and foodstuffs. This will ensure the sanitary quality of the stocks and contribute to the objective of achieving food security.

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Authors' Contributions

S.N. is a PhD student who was conducting the survey and sampling. He prepared the initial manuscript and conducted the analysis and interpretation of the results. F.H.B. is a nutrition project manager who devised the study and made a significant contribution to the writing of the manuscript. D.K. contributed to the analysis of aflatoxins in the ICRISAT laboratory. B.N. provided input into the sampling protocol. S.B. undertook the necessary corrections to the manuscript and ensured that the English was of an appropriate standard. A.S. is the principal supervisor of the work. All authors have read and approved the final manuscript in accordance with the standards of academic integrity.

Competing Interests

The authors declare no conflicts of interest.

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