Postprint: Study on Anti-Mold Efficacy of High-Performance Barrier Films During Storage of Freshly Produced Steam-Flaked Corn

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Abstract

This study utilized ordinary membranes and high-performance barrier membrane materials to store newly produced steam-flaked corn, examined mold contamination in steam-flaked corn at different storage time points, and explored the feasibility of using high-performance barrier membranes for storing newly produced steam-flaked corn. The experiment designated newly produced steam-flaked corn stored in non-sealed ordinary membranes as the non-sealed ordinary membrane group, that stored in sealed ordinary membranes as the sealed ordinary membrane group, and that stored in sealed high-performance barrier membranes as the high barrier membrane group. Steam-flaked corn from each group was sampled after storage for 0, 7, 14, 21, 28, 42, and 56 d, and subjected to sensory evaluation along with determination of chemical composition, fatty acid value, and contents of aflatoxin B1 (AFB1), zearalenone (ZEA), and deoxynivalenol (DON). The results demonstrated: 1) With prolonged storage duration, mold contamination successively appeared in the non-sealed ordinary membrane group and sealed ordinary membrane group, whereas no mold contamination was observed in the high barrier membrane group through 56 d of storage. 2) As storage days increased, crude fat, soluble starch content, and starch gelatinization degree of steam-flaked corn across different membrane treatments exhibited decreasing trends, while crude ash, crude protein, neutral detergent fiber, and acid detergent fiber contents showed no significant changes during storage ($P>0.05$). 3) Storage time exerted an extremely significant effect on the fatty acid value of steam-flaked corn ($P<0.01$); the fatty acid value in the high barrier membrane group increased most slowly, reaching 10.54 mg/kg at 56 d of storage. 4) During storage, AFB1 and ZEA contents in steam-flaked corn displayed significant upward trends with extended storage time ($P<0.05$), whereas DON content showed no significant differences among groups ($P>0.05$). At 56 d of storage, AFB1, ZEA, and DON contents in the non-sealed ordinary membrane group, sealed ordinary membrane group, and high barrier membrane group were 1.03, 0.73, and 0.01 g/L; 181.13, 170.49, and 148.19 g/L; and 1.23, 1.23, and 1.20 g/mL, respectively. These findings indicate that high-performance barrier membranes can effectively inhibit mold growth, delay fatty acid rancidity, and enable safe storage of newly produced steam-flaked corn for up to 56 d.

Full Text

Anti-Mildew Effects of High-Performance Barrier Films on Fresh Steam-Flaked Corn during Storage

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Abstract

This study investigated the feasibility of using high-performance barrier films (HPBF) to store fresh steam-flaked corn by comparing mildew development and nutritional quality changes during storage. Three treatments were evaluated: unsealed general plastic films (USGPF), sealed general plastic films (SGPF), and sealed high-performance barrier films (HPBF). Fresh steam-flaked corn samples were stored for 0, 7, 14, 21, 28, 42, and 56 days, after which sensory evaluation, chemical composition, fatty acid values, and mycotoxin contents (aflatoxin B1 [AFB1], zearalenone [ZEA], and deoxynivalenol [DON]) were determined. The results demonstrated: (1) Both USGPF and SGPF groups developed visible mildew during storage, whereas the HPBF group showed no mildew even after 56 days. (2) Ether extract (EE), soluble starch content, and starch gelatinization decreased over time across all treatments, while ash, crude protein (CP), neutral detergent fiber (NDF), and acid detergent fiber (ADF) contents remained unchanged ($P>0.05$). (3) Storage time exerted an extremely significant effect on fatty acid values ($P<0.01$), with the HPBF group showing the slowest increase, reaching only 10.54 mg/kg by day 56. (4) AFB1 and ZEA contents increased significantly with storage duration ($P<0.05$), while DON content showed no significant changes ($P>0.05$). After 56 days, AFB1, ZEA, and DON contents were 1.03, 0.73, and 0.01 g/L; 181.13, 170.49, and 148.19 g/L; and 1.23, 1.23, and 1.20 g/mL for USGPF, SGPF, and HPBF groups, respectively. These findings indicate that high-performance barrier films effectively inhibit mold growth and fatty acid rancidity, enabling safe storage of fresh steam-flaked corn for up to 56 days.

Keywords: high-performance barrier films; fresh steam-flaked corn; sensory evaluation; chemical composition; fatty acid value; mycotoxin content

Introduction

Steam flaking is a hydrothermal processing technology for grains that exposes starch granules and alters protein spatial structure through moist heat treatment and mechanical shearing, thereby increasing the contact area between starch granules, proteins, and rumen digestive fluids. This enhanced enzymatic accessibility improves nutrient absorption and utilization in animals. Previous studies have reported that steam-flaked corn increases small intestinal digestibility of starch and organic matter by 10–20% compared to dry-rolled corn, while increasing net energy value by 13–19%. For ruminants, steam flaking represents the most suitable corn processing method and has been widely adopted in dairy and beef cattle production.

However, industrially produced fresh steam-flaked corn contains high moisture content (approximately 20%), making it highly susceptible to mildew during storage. This can lead to production of various harmful mycotoxins including aflatoxin B1 (AFB1), deoxynivalenol (DON), and zearalenone (ZEA), which severely affect livestock product quality and animal health. Current industrial storage methods such as drying or adding organic acids (e.g., propionic acid) as mold inhibitors have limitations including energy waste, increased costs, short storage duration, reduced nutritional value, and impaired palatability, restricting the widespread application of steam-flaked corn.

High-performance barrier films (HPBF), manufactured by Mitsubishi Chemical (China) Trading Co., Ltd., are multilayer structures composed of gas-barrier materials combined with polyolefins that provide strong heat-sealing and moisture-barrier properties. These films exhibit high water vapor barrier properties while effectively blocking oxygen and carbon dioxide, creating an anaerobic environment after sealing. Through improved manufacturing processes, HPBF can also achieve heat and high-temperature resistance, providing a theoretical basis for storing fresh hydrothermal steam-flaked corn. This study aimed to evaluate the feasibility of using HPBF to store fresh steam-flaked corn by monitoring nutritional value changes and mildew development during storage, thereby providing a safer, more efficient, and economical storage method for the livestock industry.

Materials and Methods

1.1 Experimental Materials Fresh steam-flaked corn was obtained from Baotou Beichen Feed Technology Co., Ltd. (processing parameters: temperature 102°C, steam tank pressure 0.32 MPa, moist heat treatment 60 min). High-performance barrier film bags (350 mm × 220 mm) were provided by Mitsubishi Chemical (China) Trading Co., Ltd. General plastic film (GPF) bags (350 mm × 220 mm) were standard self-sealing bags (size 9) purchased from Beijing Zhibo Dingsheng Biotechnology Co., Ltd.

1.2 Experimental Design A single-factor experimental design was employed with three treatments and seven sampling time points, each with three replicates. Treatments included: (1) high-performance barrier film group (HPBF), (2) sealed general plastic film group (SGPF), and (3) unsealed general plastic film group (USGPF). The HPBF and SGPF groups used sealed packaging, while the USGPF group used unsealed packaging.

Approximately 60 kg of fresh steam-flaked corn was collected directly from the roller press without cooling or drying, then divided into three equal portions and packaged according to treatment (approximately 1 kg per bag). The routine chemical composition of fresh steam-flaked corn is presented in . Packaged samples were stored in the feed storage room of the Beef Cattle Research Center at China Agricultural University (temperature 16–20°C, relative humidity 45%–65%). At each time point (0, 7, 14, 21, 28, 42, and 56 days), three bags from each treatment were randomly selected, and samples were prepared using the quartering method to create air-dried samples for analysis.

1.2.1 Sensory Evaluation Prior to sample preparation at each time point, sensory evaluation was conducted following methods recommended in *Feed Analysis and Feed Quality Detection Technology* (3rd Edition).

1.2.2 Chemical Composition Analysis Moisture, dry matter (DM), ash, ether extract (EE), NDF, and ADF contents were determined according to *Feed Analysis and Feed Quality Detection Technology* (3rd Edition). EE content was measured using an ANKOM automatic fat extractor, while NDF and ADF were analyzed using an ANKOM automatic fiber analyzer. Crude protein content was determined following GB/T 24318—2009, and starch content and gelatinization degree were measured using the method recommended by Xiong Yiqiang.

1.2.3 Fatty Acid Value Determination Fatty acid values were determined according to NY/T 2333—2013 *Determination of Fatty Acid Values in Grains and Oilseeds.*

1.2.4 Mycotoxin Content Determination Mycotoxin contents were measured using enzyme-linked immunosorbent assay (ELISA). AgraQuant test kits for aflatoxin B1 (2–50 g/L), deoxynivalenol (0.25/5.00 g/mL), and zearalenone (25–1,000 g/L) were purchased from ROMER International Trade (Beijing) Co., Ltd., and analyses were performed according to manufacturer instructions.

1.3 Statistical Analysis Data were initially processed and graphed using Excel 2010, followed by two-way ANOVA using SAS 9.2. Means were compared using Duncan' s multiple range test.

Results

2.1 Sensory Characteristics of Fresh Steam-Flaked Corn During Storage At 7 days, all groups showed no mildew, exhibited bright yellow color, and possessed the characteristic fresh aroma of steam-flaked corn. The USGPF and SGPF groups contained more air inside the bags, while the HPBF group showed tighter film contraction with less air between corn particles. At 14 days, the USGPF group developed small amounts of yellow-brown mold on surfaces contacting air, with slight musty odor upon opening, whereas both SGPF and HPBF groups showed no visible mildew and maintained bright yellow color and fresh aroma.

At 21 days, the USGPF group exhibited extensive mold growth on surface layers with obvious musty odor. The SGPF group showed minor mold growth at contact points between corn surfaces and the film, with slight musty odor, while the HPBF group remained unchanged with no visible mildew. At 28 days, mildew in the USGPF group began spreading from the surface inward, with intensified odor, while the SGPF group showed expanding mold areas on surfaces. The HPBF group still showed no changes. By 56 days, the USGPF group was completely moldy, appearing dark green with clumping, visible mycelium upon opening, and severe musty odor. The SGPF group showed obvious surface mold growth, distinct musty odor, and slight moisture, whereas the HPBF group remained mold-free, maintained bright yellow color and fresh aroma, and showed no bag swelling.

2.2 Chemical Composition of Fresh Steam-Flaked Corn During Storage Chemical composition data for all groups and time points are presented in . Ash, CP, NDF, and ADF contents showed no significant differences across film treatments or storage times ($P>0.05$).

Both film treatment and storage time exerted extremely significant effects on DM content ($P<0.01$). The HPBF group maintained the lowest DM content (80.95%) throughout storage, significantly lower than the other two groups ($P<0.05$). Although DM content varied across time points, it did not show a consistent pattern with storage duration.

Film treatment and storage time also had extremely significant effects on EE content ($P<0.01$). EE content decreased markedly over time, reaching 2.96% at 56 days. The SGPF group showed the lowest EE content (3.35%) during storage, while the HPBF group maintained the highest (3.95%).

Storage time had an extremely significant effect on soluble starch content and starch gelatinization ($P<0.01$), with both parameters decreasing over time. Film treatment also significantly affected these parameters ($P<0.05$). The HPBF group maintained the highest soluble starch content (28.87%) and starch gelatinization (38.94%) throughout storage, followed by the USGPF group (28.12% and 37.81%), with the SGPF group showing the lowest values (27.70% and 37.63%).

2.3 Fatty Acid Values of Fresh Steam-Flaked Corn During Storage Fatty acid values for each group are shown in . Storage duration had an extremely significant effect on fatty acid values (P<0.01). The SGPF group showed rapid changes, increasing to 7.97 mg/kg by day 7 and peaking at 36.78 mg/kg on day 21 before declining. The USGPF group reached 6.13 mg/kg at day 14, peaked at 28.62 mg/kg on day 28, then decreased. In contrast, the HPBF group showed the slowest increase, reaching only 7.23 mg/kg at day 28.

2.4 Mycotoxin Content of Fresh Steam-Flaked Corn During Storage As shown in , storage time had an extremely significant effect on AFB1 content (P<0.01). No AFB1 was detected at day 0, but content reached 1.26 g/L by day 56. Film treatment also had an extremely significant effect (P<0.01), with the USGPF group showing the highest AFB1 content (1.03 g/L), followed by SGPF (0.73 g/L), and HPBF showing the lowest (0.01 g/L).

Storage time significantly affected ZEA content (P<0.05), increasing from 152.15 g/L at day 0 to 194.85 g/L at day 56. Film treatment also significantly influenced ZEA content (P<0.05), with mean values of 181.13, 170.49, and 148.19 g/L for USGPF, SGPF, and HPBF groups, respectively.

Neither storage time nor film treatment significantly affected DON content (P>0.05). DON content changed from 1.18 g/mL at day 0 to 1.25 g/mL at day 56, with values of 1.23, 1.23, and 1.20 g/mL for USGPF, SGPF, and HPBF groups, respectively.

Discussion

3.1 Sensory Characteristics Analysis Both USGPF and SGPF groups developed mold growth as storage progressed. The USGPF group, with greater air exposure, showed mold initiation at 14 days. General plastic films provided some air barrier effect, slowing surface mold growth compared to the unsealed treatment. The HPBF packaging was notably tighter, likely due to reduced internal pressure as the hot, moist corn cooled after sealing, demonstrating good heat-shrink properties and thermal stability. The absence of mold in the HPBF group through 56 days confirms that HPBF effectively prevents external air entry, exhibiting excellent gas barrier performance.

3.2 Chemical Composition Analysis The HPBF group maintained the lowest DM content (highest moisture) throughout storage, while the other two groups showed lower moisture content, likely due to water consumption by mold activity. The significant decreases in EE and soluble starch content in USGPF and SGPF groups resulted from mold proliferation, as these nutrients serve as primary substrates for fungal growth. The HPBF group retained the highest EE and soluble starch contents, indicating suppressed mold activity compared to the other treatments.

The reduction in soluble starch content decreased glucose release, consequently lowering starch gelatinization, consistent with findings by Zhang et al. The stable contents of ash, CP, NDF, and ADF during storage align with previous studies by Wei et al. and Bartov et al. Notably, the HPBF group showed slower declines in EE and soluble starch, with significant differences emerging by days 28 and 21, respectively, confirming minimal mold infection and effective fungal growth inhibition, which corroborates sensory evaluation results.

3.3 Fatty Acid Value Analysis Fatty acid value (or acid value) serves as a key indicator of lipid rancidity in stored grains and oilseeds, with lower values indicating less spoilage. The observed increases across all groups confirm mold infection and lipase-mediated hydrolysis of fats into free fatty acids. According to GB/T 20570—2006, corn with fatty acid values $ $5.00 mg/kg is suitable for storage, $ $7.80 mg/kg is marginally unsuitable, and >7.80 mg/kg is severely unsuitable. The USGPF group reached 6.13 mg/kg by day 14, and the SGPF group reached 7.97 mg/kg by day 7, both becoming unsuitable for continued storage. In contrast, the HPBF group only reached 7.23 mg/kg at day 28, demonstrating effective suppression of fatty acid value increase, likely due to HPBF' s oxygen barrier properties limiting mold proliferation.

The initial increase followed by decrease in fatty acid values for USGPF and SGPF groups matches patterns reported by Wei et al. and Hu et al. The early increase reflects fat hydrolysis, while the later decrease may result from fatty acid volatilization or microbial utilization. The faster increase in the SGPF group compared to USGPF corresponds with its lower EE content, possibly because sealed general films provided poor gas barrier properties, allowing some air entry while restricting air circulation, causing localized temperature increases that accelerated rancidity. Additionally, localized oxygen depletion may have promoted anaerobic fermentation and lactic acid production, further increasing fatty acid values.

3.4 Mycotoxin Content Analysis AFB1 content increased with storage time but remained relatively low despite severe visible mold, consistent with findings by Wei et al., Qi et al., and Huang et al. The USGPF group showed the highest AFB1 content (1.03 g/L), followed by SGPF (0.73 g/L), with HPBF showing the lowest (0.01 g/L), reflecting faster Aspergillus growth in unsealed conditions. Although all groups remained below China's food safety standard of 20 g/L for corn and corn products, the HPBF group only reached 0.22 g/L at day 56, demonstrating superior AFB1 suppression and potential for long-term safe storage. The lower AFB1 levels compared to Wei et al.' s study (5–20 g/L) may be attributed to inactivation of Aspergillus during the high-temperature steam flaking process.

Zearalenone, a secondary metabolite of Fusarium species that affects estrogen production and reproductive health, showed slow increases during storage, likely because it is a field toxin whose production depends on numerous factors not easily replicated in laboratory conditions or requiring longer storage periods for significant accumulation. The slow increase aligns with Wei et al.' s findings, and all groups remained below China' s feed hygiene standard of 500 g/L.

Deoxynivalenol (DON), a highly toxic B-type trichothecene produced by Fusarium species that causes kidney damage and vomiting, showed no significant differences among groups or changes during storage. Initial DON levels (0.92–1.52 g/mL) exceeded 1 g/mL at day 0, indicating pre-existing fungal infection in the raw corn, consistent with Zhen et al.' s findings of widespread DON contamination in Chinese feed ingredients (95.8% detection rate, 17.7% exceeding 1 g/mL). While China has established DON limits for compound feeds (1 g/mL for pigs, calves, and lactating animals; 5 g/mL for cattle and poultry), no limits exist for feed ingredients except dried distillers grains. FDA advisory levels recommend 1 g/mL for swine feed, 2 g/mL for other animal feeds, and 5–10 g/mL for grain ingredients in cattle and poultry feeds.

Conclusion

This study demonstrates that high-performance barrier films provide effective protection for fresh steam-flaked corn during storage. Key findings include: (1) All packaging treatments showed decreasing trends in EE, soluble starch content, and starch gelatinization over time, while ash, CP, NDF, and ADF contents remained stable. (2) HPBF packaging effectively delayed fatty acid rancidity and inhibited mold growth, enabling safe storage of fresh steam-flaked corn for 56 days. (3) HPBF technology offers significant potential for industrial application by extending storage duration and reducing losses associated with drying processes in steam-flaked corn production.

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Note: Figure translations are in progress. See original paper for figures.