Stability of α-Linolenic Acid and Secoisolariciresinol Diglucoside in Flaxseed-Fortified Macaroni

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ABSTRACT: Research was conducted to determine the stability of secoisolariciresinol diglucoside (SDG) and α-linolenic acid (ALA) in flaxseed-fortified macaroni. Macaroni was fortified with whole ground flaxseed (GWF) at levels of 10% to 20% and then dried under low temperature (LT, 40 °C), high temperature (HT, 70 °C), or ultrahigh temperature (UHT, 90 °C). Macaroni was also fortified with 15% ground hull (GHF) or steam-treated whole ground flaxseed (GSWF) and dried under UHT. The dried macaroni was stored for 32 wk under ambient conditions. Approximately 80% to 95% of the SDG was recovered, indicating that SDG was stable during the 32-wk storage period. Total lipid and ALA levels in all flaxseed macaroni treatments remained unchanged throughout the 32-wk storage. This observation was consistent across the drying conditions and flaxseed addition levels. Conjugated diene (CD) values indicated that macaroni fortified with GWF did not oxidize significantly during the 32-wk storage for the macaroni dried under HT or UHT. However, a significant increase ($P < 0.05$) in CD values for macaroni containing 10% and 20% flaxseed and dried using LT was observed at the 32-wk storage period. Headspace volatile concentrations did increase over the storage period for macaroni containing GWF, but the increase was not significant. Significant increases ($P < 0.05$) in oxidation were found by 24 wk in GHF- and GSWF-fortified macaroni. GWF macaroni dried at UHT, HT, or LT could be used as a way to improve our dietary consumption of ALA and SDG. However, use of steam as a method to inactivate unwanted enzyme activity is not recommended.

Keywords: flaxseed, macaroni, oxidative stability, secoisolariciresinol diglucoside (SDG), α-linolenic acid (ALA)

Introduction

Functional foods have been defined by the Food and Nutrition Board of the Natl. Academy of Sciences as "any modified food or food ingredient that may provide a health benefit beyond that of the traditional nutrients it contains" (Thomas and Earl 1994). Associated with the rapid increase in the interest in functional foods is a lack of understanding of how the active components "function" in food systems and in health promotion. Processing can affect the activity of the bioactive compounds. The complexity of food systems does not lend itself to a "one size fits all" rationale; thus more information is needed to provide support for the development of functional foods. In addition, identification and quantification of bioactive compounds in finished products is necessary if functional foods are to have an impact on human health.

Flaxseed (*Linum usitatissimum* L.) is a rich source of the lignan secoisolariciresinol diglucoside (SDG), α-linolenic acid (ALA [18:3n-3]), and dietary fiber (Dorrel 1970; Thompson and others 1991). SDG is the predominant lignan found in flaxseed. The lignans of flaxseed are phytoestrogens and serve as precursors in the production of mammalian lignans. Flaxseed lignans are converted to the mammalian lignans enterolactone and enterodiol by intestinal flora (Axelson and Setchell 1981; Adlercreutz and others 1982; Axelson and others 1982), where they are believed to protect against hormone-sensitive cancers (such as breast, prostate, and colon) by reducing estrogen availability (Thompson and others 1996, 1997; Westcott and Muir 2000).

Flaxseed contains 40% to 60% lipid, in which about 50% is ALA (Dorrel 1970). ALA, a short-chain omega-3 fatty acid, is the precursor fatty acid for the synthesis of eicosapentaenoic acid (EPA [20:5n-3]) and docosahexaenoic acid (DHA [22:6n-3]), which both have been linked to controlling cardiovascular diseases (Goodnight 1993; Bibus and others 1998; Simopoulos 1999). ALA has been associated with reduced levels of low-density lipoprotein (LDL) in the blood serum (Pszczola 1998). Leading health organizations agree that a 5:1 ω-6 to ω-3 fatty acid ratio is preferred (Hauman 1998). However, a typical western diet has a 10:1 ω-6 to ω-3 fatty acid ratio; thus, flaxseed with its high ω-3 fatty acid content can be a valuable lipid source to improve the ω-6 to ω-3 fatty acid ratio.

Full-fat flaxseed meal enhanced the cholesterol-lowering effect of diets containing flaxseed oil. Cunnane and others (1993) reported a 9% reduction in cholesterol (18% for LDL) in females fed 50 g of flaxseed per day. Jenkins and others (1999) also noted a reduction in serum LDL levels in subjects fed partially de-fatted flaxseed. These researchers attributed the LDL reduction to the gum (namely, soluble fiber) component of the flaxseed. Arjmandi and others (1998) reported a 6.9% reduction in cholesterol of postmenopausal women fed 38 g flaxseed per day. A 14.7% reduction in serum LDL was noted, whereas serum HDL and TAG were not affected. A 7.4% reduction in apoprotein A, a marker for cardiovascular disease, level was also noted in postmenopausal women. By incorporating flaxseed into a daily diet, a person could benefit from the aforementioned health effects. These studies demonstrate the benefits of flaxseed; however, few reports exist regarding the stability of flaxseed in processed foods.

Research conducted by Muir and Westcott (2000) showed that the

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breadmaking process did not affect SDG stability. However, SDG recovery from the bread was only 73% to 75% of the theoretical yield. Gluten formation during breadmaking could entrap the flaxseed and interfere with SDG recovery, which might lead to a low SDG yield.

Malcolmson and others (2000) reported that milled flaxseed, stored at ambient temperature in plastic-lined, triple-layered paper bags was stable for 128 d. Peroxide values, conjugated dienes, and headspace volatiles remained constant during the 128-d investigation. A more comprehensive investigation by Chen and others (1994) reported that milled flaxseed particles between 20 μm and 950 μm were the most oxidatively stable.

Manthey and others (2002) and Lee and others (2003, 2004) reported that pasta processing did not alter fatty acid profiles or oxidative stability of lipids in pastas containing up to 20% flaxseed. However, these studies did not report long-term lipid stability of the flaxseed pastas. We hypothesize that the incorporation of components with high lipid content may reduce shelf life of pasta due to oxidative rancidity. Thus, the objective of this research was to determine shelf life stability of macaroni containing ground whole flaxseed, ground steamed whole flaxseed, and ground-flaxseed hulls. A 2nd hypothesis was that the high-temperature processing could negatively affect SDG stability. Thus, the 2nd objective was to determine the stability of SDG in the aforementioned pastas.

Materials and Methods

Sample preparation

Commercial semolina was obtained from the North Dakota Mill and Elevator (Grand Forks, N.Dak., U.S.A.). 'Omega' flaxseed was obtained from Reimers Seed Co. (Carrington, N.Dak., U.S.A.). Flaxseed hulls were obtained using a pearling procedure described and developed by Tostenson and others (2000). Steamed whole flaxseed was prepared by exposing the whole flaxseed to steam at 100 °C for 15 min. The sample was then dried at 60 °C to a moisture content of about 8%. Flaxseed hulls, steamed whole flaxseed, and whole flaxseed were ground on an Urschel Comitrol mill (Urschel Laboratories, Valparaiso, Ind., U.S.A.) and then sieved according to the method of Manthey and others (2002). The ground flaxseed that passed through the number 34XXGG sieve (531 μm) was collected and used to make flaxseed macaroni. The ground whole flaxseed was mixed with semolina at 10%, 15%, and 20% W/W. Semolina was fortified with 15% W/W ground flaxseed hulls and ground steamed whole flaxseed. Semolina-flaxseed mixtures were mixed for 5 min using a cross-flow blender before extrusion.

Macaroni processing and shelf life sampling parameters

Semolina-flaxseed mixtures were hydrated to 30% moisture and extruded as macaroni using a semicommercial laboratory extruder (Manthey and others 2002; Lee and others 2003). The macaroni was dried in a laboratory pasta dryer using a LT (40 °C), HT (70 °C), or UHT (90 °C) drying cycle (Yue and others 1999). After drying, the flaxseed macaroni (55 g) was placed in 10- × 15-cm plastic bags. Each plastic bag had 3 (5-mm dia) holes punched through it so that the flaxseed macaroni was exposed to ambient conditions (23 ± 3 °C; 30% ± 5% relative humidity) away from light. Each treatment was sampled every 2 wk for the 1st 12 wk and then every 4 wk for the following 20 wk. The total duration of the shelf life study was 32 wk.

Oil recovery and analysis

Crude oil content in ground samples (50 g) was determined using a 16-h Soxhlet extraction with hexane. Fatty acid composition of extracted oil was determined following the method of Manthey and others (2002). Oil oxidation was determined by using a modified conjugated dienoic acid (CD) method (AOCS 1998). Secondary oxidation products were measured using modified headspace solid-phase microextraction (SPME; Steenson and others 2000). In short, ground macaroni (1 g) was placed in 4-mL vials and sealed using Teflon-faced silicone septa, which previously had been heated at 100 °C for 24 h before use. The sample was heated in a 99 °C water bath for 20 min, and the SPME filament (polydimethylsiloxane filament,100 μm; Supelco, Bellefonte, Pa., U.S.A.) inserted into the vial. The SPME filament remained in the headspace for 2 min and was then transferred to the GC and allowed to desorb for 3 min. The GC system included an HP5890 gas chromatograph with a flame ionization detector and equipped with a DB-1701 column (30 m × 0.32-mm inner dia; Agilent Technologies Inc., Palo Alto, Calif., U.S.A.). The volatile analysis was completed under the following conditions: helium flow rate of 33.7 mL/min; initial oven temperature of 40 °C ramped to 180 °C at 10 °C/min and held 12 min at 180 °C. The volatiles evaluated included propanal, pentane, hexanal, 2t- and 3c-hexenal, heptadienal, octanal, and nonanal. These volatiles were selected based partly on the findings of Malcolmson and others (2000), Jelen and others (2000), and on the anticipated secondary oxidation products of ALA. Retention times were based on standards obtained from Aldrich Chemical Co. (Milwaukee, Wis., U.S.A.).

SDG recovery and analysis

SDG recovery from pasta containing flaxseed was determined using a modified method of Muir and Westcott (2000). Defatted ground macaroni, obtained from the oil extraction step, was used to determine SDG content. Defatted ground macaroni meal (1.0 g) was mixed with deionized distilled water (3 mL) containing papain (50 mg/mL; 6000 units/mg; pH 6.1 to 6.3; DIFCO Laboratories; Detroit, Mich., U.S.A.) and placed in an air-current incubator for 30 min at 60 °C. Methanol (7 mL) was then added to each sample and the mixture subjected to continuous agitation for 3 h at 60 °C. The mixtures were then cooled to room temperature and centrifuged at 4100 rpm for 20 min. An aliquot (2 mL) from each sample was mixed with 0.5 *N* NaOH (0.5 mL) and hydrolyzed for 3 h at room temperature. Each aliquot was neutralized with 0.86 *N* acetic acid (0.5 mL), which resulted in a pH of 6.0. Finally, each aliquot was passed through a 0.45-μm nylon membrane micro-filter into vials.

The SDG content was measured using a Hewlett-Packard (HP) 1090 high-performance liquid chromatograph (Agilent Technologies Inc.) system equipped with LiChrosphere 100 RP-C18 column (5 μm, 250 mm × 4.5 mm; Agilent Technologies Inc.). Separation was carried out under the following conditions: injection volume of 10 μL; column flow rate of 1 mL/min; column temperature at 40 °C; and detection at 280 nm. The samples were eluted with a 1% acetic acid (solvent A) and 100% methanol (solvent B) gradient (t = 0 min, A = 95%, B = 5%; t = 44 min, A = 40%, B = 60%; t = 48 min, A = 40%, B = 60%; t = 55 min, A = 95%, B = 5%). SDG was confirmed by its retention time and quantified on a nonfat, dry basis against peak area standard plots of known SDG concentrations.

Statistical analysis

The experimental design was a random complete block with a split-plot in time arrangement. Whole plots were drying temperature and subplots were treatments. Treatments consisted of 0%, 10%, 15%, and 20% ground flaxseed dried at LT, HT, or UHT, and macaroni containing 15% ground hull and 15% ground steamed flaxseed (wt/wt) were dried at only ultrahigh temperature. Each treatment was replicated 3 times with a separate batch of semolina-flaxseed mixture representing a replicate. For each replicate, the analyses were duplicated. Treatment means were subjected to linear regression and analysis of variance.

Means were separated by Fisher's Protected least significant difference (LSD) at the $P \leq 0.05$ probability level.

Results and Discussion

Lipid stability

Presented in Table 1 are the fatty acid profiles and total lipid contents of the various macaroni samples. The total lipid content of the 15% ground hull flaxseed (GHF)-fortified macaroni was 33% lower than the 15% ground whole flaxseed (GWF)-fortified macaroni. Data were in agreement with those of Madhusudhan and others (2000) and Tostenson and others (2000), who showed that flaxseed hull had approximately 34% to 37% less lipid in the hull. The total lipid contents in the macaroni samples were in agreement with the predicted values, and differences in the data were simply due to the varying amounts of flaxseed added to the pasta formulas.

Our initial concern over the oxidative stability was based on research that showed that lipoxygenase, an enzyme that promotes oxidation of lipids, from durum wheat could remain active during pasta processing (Irvine and Winkler 1950; Borrelli and others 1999). Furthermore, flaxseed contains lipoxygenase (Zimmerman and Vick 1970; Oomah and others 1997), which could remain active during pasta processing. In contrast, the dry pasta would have little or no lipoxygenase activity because of the low moisture content and partial deactivation of the enzymes during drying (Fox and Mulvihill 1982). We (Manthey and others 2002; Lee and others 2003) reported that lipid oxidation did not increase significantly during the mixing, extrusion, and drying stages of pasta processing. However, long-term storage was not addressed, nor was the issue of pretreatment of the flaxseed before addition to pasta formulas. Thus, our 1st objective in this study was to evaluate the lipid stability of pasta fortified with flaxseed.

The concentration of lipids extracted from the flaxseed macaroni treatments remained unchanged throughout the shelf life study. For example, the pasta containing 20% flaxseed had an average lipid content of 101.4 mg/g dry macaroni with levels ranging from 98 to 103.5 mg/g (data not shown). No statistically significant differences were found in the lipid content within each treatment during the entire 32-wk study. The ALA levels also remained constant over 32 wk, and no statistical differences were found during the study (Table 2). Similar trends were found in macaroni containing less flaxseed. The stability of ALA during macaroni processing agreed with results of Chen and others (1994) who noted that ALA remained stable during breadbaking. The data suggest that ALA can be delivered via pasta products.

All macaroni samples were relatively stable toward oxidation during the 32-wk study. CD values through week 20 of storage were not significantly different from the time zero values for any treatment, including drying temperature. However, CD value increased at the 24-wk measurement for 10% WGF, 15% GHF, and 15% GSWF dried using UHT (Table 3), and at week 32 for 10% WGF, 15% WGF, and 20% WGF dried using LT (Table 4). The CD data (0.20% to 0.40%) for the pasta containing whole ground flaxseed were similar to CD data (0.19% to 0.31%) reported by Malcolmson and others (2000) for stored ground flaxseed.

In general, most of the volatiles analyzed using SPME increased over the course of the 32-wk storage (Figure 1 through 3). However, no clear relationship existed between the CD, headspace volatiles, and treatment. For example, 15% GSWF had the highest CD value (0.62%) at 32 wk but had a volatile profile similar to 15% GWF, which had significantly lower CD (0.32%; Figure 3, Table 3). Additional time may be required to observe a pronounced volatile formation. For example, we observed a hexanal level as high as 3600 ppb in a flax-

Table 1—Lipid content (mg/g, db) and fatty acid distribution of lipids in flaxseed-macaroni dried at ultrahigh temperature

Treatment / Fatty Acid	0% GWF[b]	10% GWF	15% GWF	20% GWF	15% GHF[c]	15% GSWF[d]
Palmitic	0.6	3.5	4.8	5.9	4.1	4.9
Stearic	0.1	1.6	2.5	3.3	0.9	2.4
Oleic	1.0	11.9	17.6	23.0	12.3	17.7
Linoleic	1.9	12.1	16.6	20.3	11.1	16.7
Linolenic	0.9	22.2	34.7	48.0	23.4	35.3
Total	4.5	51.3	76.3	100.5	51.8	77.0

[a]The comparison is by time (wk) within a treatment concentration at a specific drying temperature. Means within a row followed by no letter or the same letter are not different at $P \leq 0.05$.
[b]GWF = ground whole flaxseed.
[c]GHF = ground hull flaxseed.
[d]GSWF = ground steamed whole flaxseed.

Table 2—Alpha-linolenic acid concentration (mg/g, db) of macaroni fortified with 20% flaxseed and dried under various temperatures and stored 32 wk

	Weeks					
Drying method[a]	0	2	6	12	20	32
Low temp	48.1	47.5	47.1	47.1	46.8	47.7
High temp	47.3	46.7	45.7	45.0	45.8	47.5
Ultrahigh temp	47.9	46.9	46.2	44.7	45.8	45.8

[a]Drying method refers to the method in which the extruded macaroni was dried.

Table 3—Conjugated diene values (%) from flaxseed-macaroni dried at ultrahigh temperature and stored at ambient conditions for 32 wk

Time[a]	10% GWF[b]	15% GWF	20% GWF	15% GHF[c]	15% GSWF[d]
Week 0	0.29abc	0.25	0.25	0.26a	0.21ab
Week 4	0.28ab	0.24	0.24	0.28ab	0.24abc
Week 8	0.25a	0.23	0.22	0.26a	0.20ab
Week 12	0.28a	0.24	0.23	0.27ab	0.22ab
Week 16	0.30abc	0.26	0.26	0.30ab	0.26abc
Week 20	0.29abc	0.25	0.23	0.28ab	0.27bc
Week 24	0.35bc	0.26	0.24	0.34b	0.33c
Week 32	0.36c	0.32	0.29	0.48c	0.62d

[a]The comparison is by time (week) within a treatment concentration at a specific drying temperature. Means within a column followed by no letter or the same letter are not different at $P \leq 0.05$.
[b]GWF = ground whole flaxseed.
[c]GHF = ground hull flaxseed.
[d]GSWF = ground steamed whole flaxseed.

Table 4—Conjugated ciene values (%) from flaxseed-macaroni dried at low or high temperature and stored at ambient conditions for 32 wk

	10% GWF[b]		15% GWF		20% GWF	
Time[a]	LT[c]	HT	LT	HT	LT	HT
Week 0	0.28ab	0.27	0.26ab	0.26	0.22a	0.24a
Week 4	0.25a	0.28	0.24a	0.25	0.23a	0.25a
Week 8	0.28ab	0.25	0.24a	0.22	0.22a	0.22a
Week 12	0.27ab	0.26	0.23a	0.23	0.22a	0.22a
Week 16	0.27ab	0.26	0.24a	0.24	0.23ab	0.23a
Week 20	0.27ab	0.25	0.26ab	0.23	0.23ab	0.23a
Week 24	0.32b	0.27	0.25a	0.25	0.24ab	0.21a
Week 32	0.40c	0.33	0.33b	0.27	0.30b	0.36b

[a]The comparison is by time (week) within a treatment concentration at a specific drying temperature. Means within a column followed by no letter or the same letter are not significantly different at $P \leq 0.05$.
[b]GWF = ground whole flaxseed.
[c]Drying condition: LT = low temperature, HT = high temperature.

seed spaghetti sample stored 2 y (data not shown), suggesting that the flaxseed pasta does not have an indefinite shelf life. Regardless of drying temperature, pentane was present at high concentrations relative to the other volatile compounds tested (Figure 1 through 3). However, the low-temperature-dried macaroni generally had higher levels of volatiles compared with high-temperature-dried and ultra-high-temperature-dried macaroni. The lower volatiles present in HT and UHT dried samples might reflect the inactivation of lipoxygenase via denaturation of the enzyme during drying. Furthermore, the stored samples tended to have higher volatile concentrations than the zero time samples.

In general, the macaroni made with the steam-treated flaxseed and hulls appeared to be less stable to lipid oxidation. Steam treatment of the flaxseed resulted in a lower volatile profile initially; however, significant increases in the volatiles of the 15% GSWF macaroni were observed by the end of 32 wk of storage (Figure 3). The volatiles may have evaporated during the steaming process, but the steam treatment may have affected the flaxseed, thus resulting in the increased susceptibility of the GSWF macaroni to oxidation. We expected that a steam treatment of ground flaxseed would diminish free fatty acid formation and lipid oxidation by inactivating lipase (>50 °C) and lipoxygenase (>68 °C) (Rajeshwara and Prakash 1996; Barone and others 1999). The CD, free fatty acids, or fatty acid composition (data not shown) of the original flaxseed were not affected by the steaming process, thus minimal lipase or lipoxygenase activity was present in the flaxseed. However, if wheat enzymes remain active during the mixing, extrusion, and initial stages of drying, the degradation of triacylglycerides and oxidation of the lipids could be promoted. As stated previously, oxidative indices showed initially that steaming had little impact on oxidation stability; however, oxidative stability was greatly reduced during the later phases of storage. This suggests that the lipase and lipoxygenase may not have been a factor in promoting oxidation. The steam treatment could possibly predispose the oil to autoxidation because heating has been shown to enhance lipid oxidation. The oil bodies (spherosomes) in flaxseed may have a barrier such as proteins that serve to protect the ground flaxseed from oxidizing. However, the steam treatment may be sufficient to denature protein, which would then allow flaxseed lipids to be exposed to the surrounding environment. The free lipid may not be incorporated as readily into the gluten network and thus undergoes oxidation during storage.

Macaroni containing the ground hull fraction tended to have higher volatiles, except propanal and heptadienal, compared with macaroni containing whole ground flaxseed. This trend was observed in both time zero and week 32 samples. When comparing the various flaxseed additions at a 15% level, the instability cannot be attributed to the level of ALA or oil content. For example, the GWF, GHF, and GSWF at 15% had oil contents of 76, 52, and 77 mg/g macaroni, where ALA accounted for 45% of the fatty acids in each of the extracted oils. Contrary to expectations, the GHF and GSWF samples at 32 wk had higher CD and total volatile values than the pasta containing GWF. Originally we believed that the lower oil and higher phenolic content in the hull fraction would prevent oxidation; however, the results are more in line with the prooxidant activity of phenols reported by Fukumoto and Mazza (2000).

SDG stability

Based on the structure of SDG, secoisolariciresinol (SECO) would be the most likely breakdown product of SDG and would be formed by the hydrolysis of glucose units from SDG. Under acidic conditions,

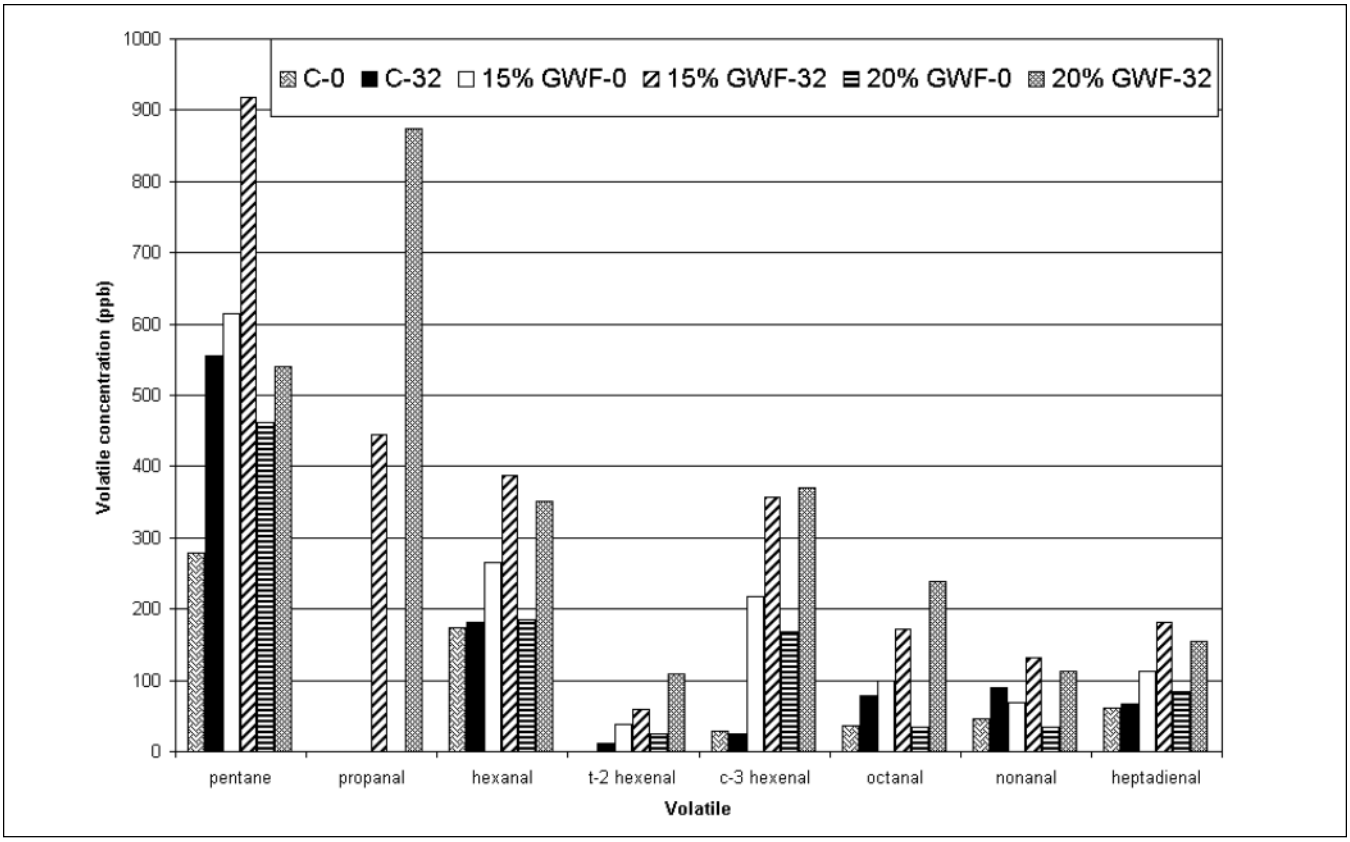

Figure 1—The volatile profile of low-temperature-dried macaroni with added ground flaxseed (GWF) or without flaxseed (C) at time 0 and stored 32 wk

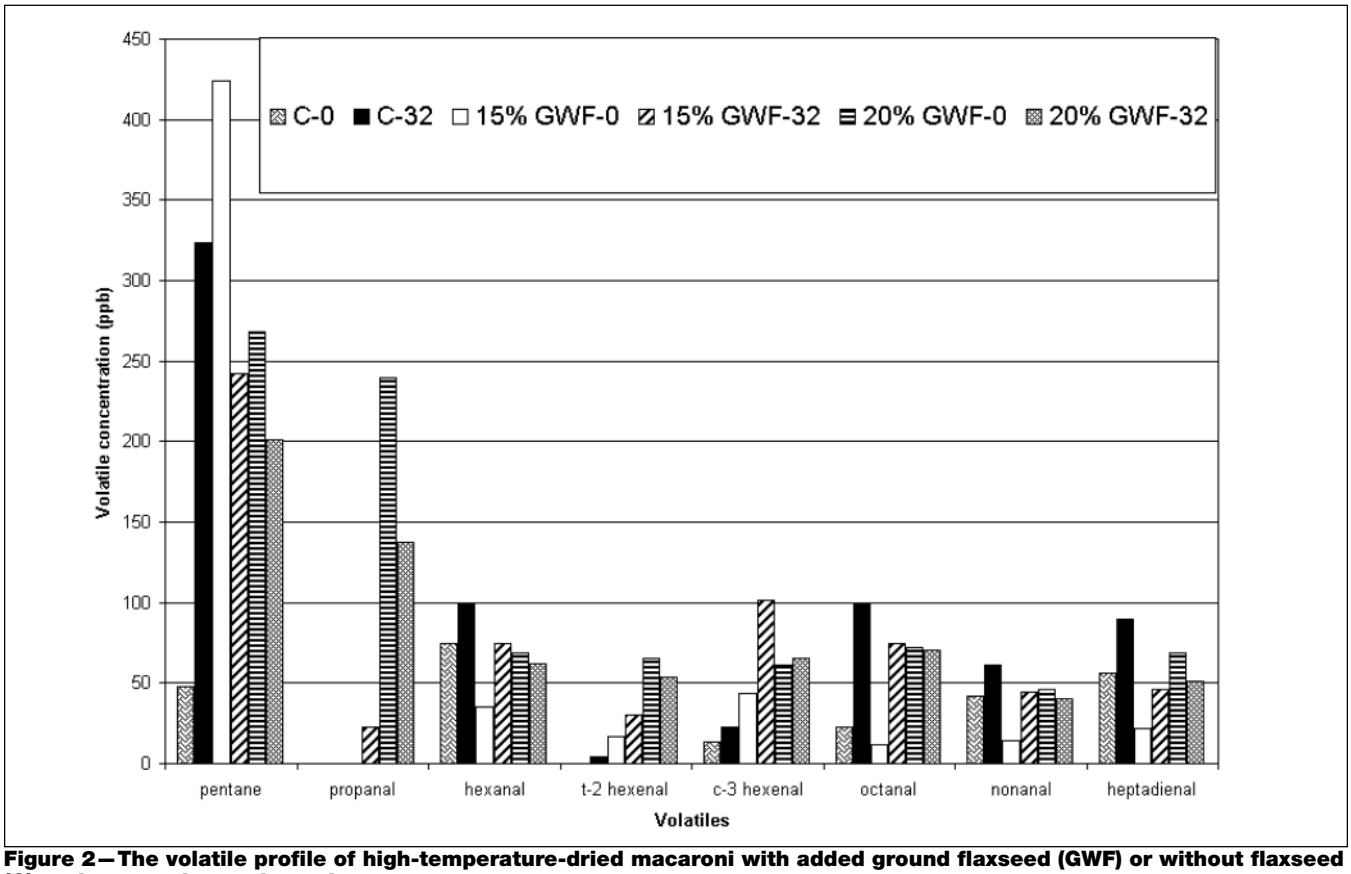

Figure 2—The volatile profile of high-temperature-dried macaroni with added ground flaxseed (GWF) or without flaxseed (C) at time 0 and stored 32 wk

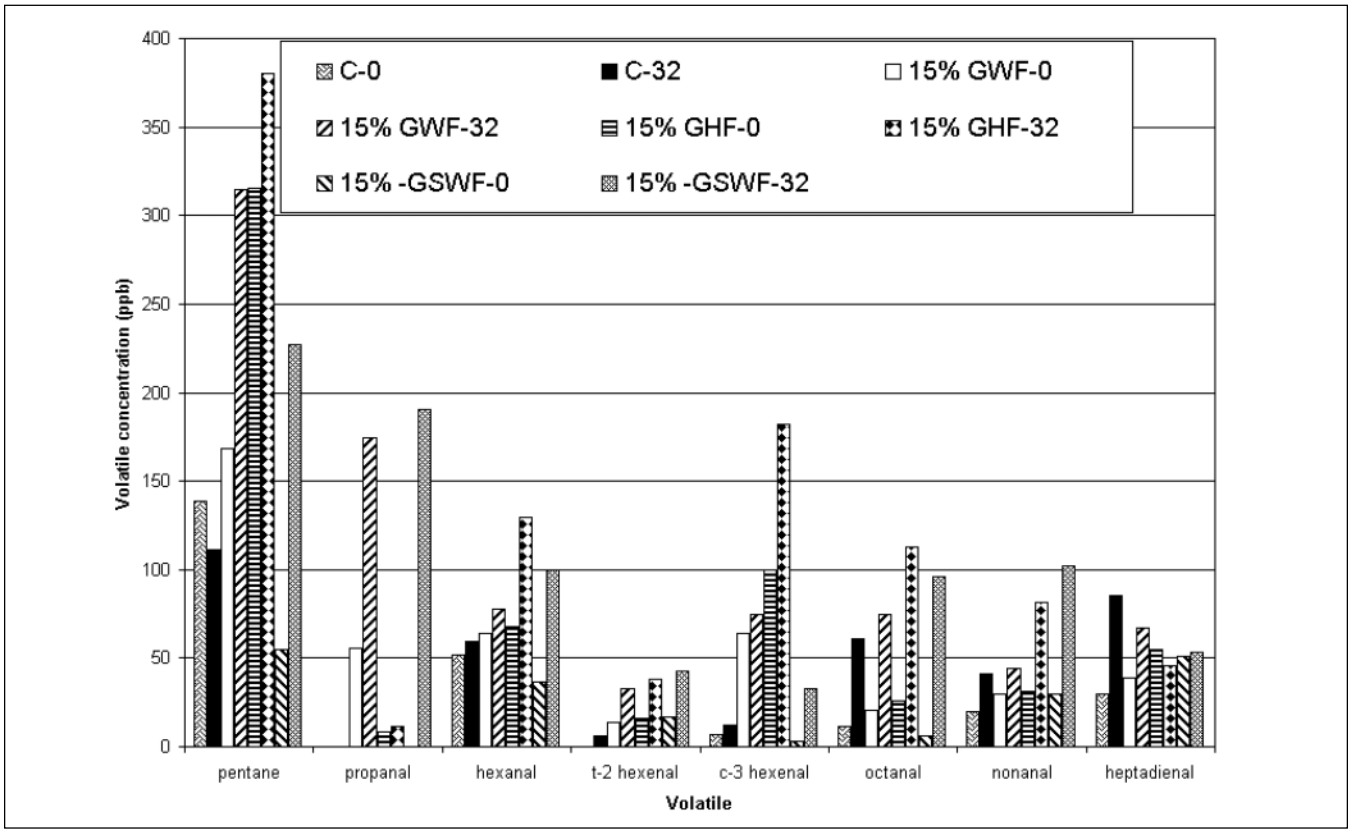

Figure 3—The volatile profile of ultrahigh-temperature-dried macaroni with added ground flaxseed (GWF), ground hull (GHF), ground steam flaxseed (GSWF), or without flaxseed (C) at time 0 and stored 32 wk

glycosidic bonds of SDG could hydrolyze to form SECO (Muir and Westcott 2000). The detection of SECO in flaxseed macaroni would indicate that SDG was not stable. No SECO was identified in the macaroni samples regardless of treatment and storage time (Table 5). The reason for this might be due to lack of acidity in the dough. The dough pH (6.0 to 6.5) was not acidic enough to hydrolyze the glycosidic bonds of SDG; thus, the conversion of SDG to SECO did not occur.

Muir and Westcott (2000) developed a procedure that recovered and purified SDG from flaxseed and baked goods. They reported a 73% to 75% recovery of the theoretical yield of SDG in baked goods. Gluten formation during breadmaking could entrap the flaxseed and interfere with SDG recovery, which might lead to a low yield of SDG. In our study, a modified procedure to recover SDG from macaroni was used. The modified SDG extraction method improved SDG recovery (80% to 96%) from pasta. The best recovery was observed in the UHT-dried macaroni. Without the papain digestion, only 40% to 50% (data not shown) of the SDG theoretical yield was recovered. The wide SDG recovery range (Table 5) could possibly be due to how quickly papain hydrolyzes potential cleavage sites and accessibility of these cleavage sites in the gluten matrix. The SDG extraction is likely affected by the breakdown of the gluten network, which entraps the flaxseed particles. The more hydrolysis, the more SDG would be recovered. The entrapment of the flaxseed and lack of protein hydrolysis may prevent the extraction of SDG. Compared with traditional macaroni, baked goods have a less dense gluten matrix, which may be the reason Muir and Westcott (2000) achieved 73% to 75% recovery of SDG compared with our 40% to 50% using their extraction protocol. Our modified extraction method does illustrate the potential to improve SDG recovery in gluten-based foods.

In summary, pasta processing and drying methods did not affect lipid oxidation as much as the pretreatment of the flaxseed with steam or addition of the hull component. The hull and steamed treatments had greater levels of oxidation than GWF. Thus, these treatments may not be appropriate pasta additives. The UHT and HT drying methods appeared to be slightly better than LT for drying pasta. However, similar trends in the oxidation data were found in all drying methods. By week 32, the samples did show early signs of oxidation but no detectable off-aroma was found. The addition of ground flaxseed to pasta did not cause significant oxidation to the pasta by 8 mo, thus demonstrating the practical application of flaxseed to pastas. However, the shelf life of the pasta was limited as observed by high hexanal levels in pasta stored over 2 y. Based on the research conducted by Malcolmson and others (2000), flaxseed sensory panelists did not detect any flavor differences between bread prepared with fresh or stored flaxseed. We found that the volatile concentrations were similar to those reported by Malcolmson and others (2000), thus macaroni containing ground flaxseed would be expected to have similar sensory properties.

Low SDG recovery without a protease pretreatment of the samples supports the flaxseed-gluten entrapment hypothesis. There are many potential reasons minimal lipid oxidation and structural breakdown of SDG did not occur during storage. These include possible protection of the lipid by native proteins of the flaxseed via an encapsulation of the oil body, gluten formed during dough extrusion entrapping the ground flaxseed, the presence of a vacuum during extrusion, and the presence of antioxidants in durum wheat and flaxseed.

Conclusions

Our results indicate that macaroni containing ground flaxseed and dried at high temperature had the best lipid stability and would provide a food product that could be used as a means to enhance dietary ALA and SDG consumption. However, use of steam as a method to inactivate unwanted enzyme activity also proved to be detrimental to flaxseed macaroni stability and is thus not recommended as a pretreatment for flaxseed.

Table 5—Secoisolariciresinol diglucoside recovery (μg SDG/g macaroni, db) after 32 wk of storage

	Week 0[a]		Week 32	
	SDG extracted (μg/g)	SDG extracted (% of T.Y.)	SDG extracted (μg/g)	SDG extracted (% of T.Y.)
Low temperature				
0% GWF[c]	0	0.0	0	0.0
10% GWF	835a	80.1	893a	87.8
15% GWF	1378a	87.8	1312a	84.5
20% GWF	1781a	86.1	1852a	90.4
High temperature				
0% GWF	0	0.0	0	0.0
10% GWF	779a	75.3	862a	84.0
15% GWF	1353a	88.2	1443a	95.5
20% GWF	1718a	82.9	1834a	88.9
Ultrahigh temperature				
0% GWF	0	0.0	0	0.0
10% GWF	851a	83.0	968a	93.3
15% GWF	1422a	91.9	1492a	96.8
20% GWF	1735a	81.8	1965a	95.5
15% GFH[d]	3295a	92.3	3313a	93.8
15% GSWF[e]	1576a	81.6	1685a	86.2

[a]The comparison is by time (week) within a treatment concentration at a specific drying temperature. Means within a row followed by the same letter are not different at $P \leq 0.05$.
[b]T.Y. = theoretical yield.
[c]GWF = ground whole flaxseed.
[d]GHF = ground hull flaxseed.
[e]GSWF = ground steamed whole flaxseed.

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