# Counteracting Roles of Lipidic Aldehydes and Phenolic Antioxidants on Soy Protein Oxidation Defined by a Chemometric Survey of Solvent and Mechanically Extracted Soybean Meals

**Junwei Zhang [1], Pedro E. Urriola [2], Seth L. Naeve [3], Gerald C. Shurson [2,*] and Chi Chen [1,*]**

[1] Department of Food Science and Nutrition, University of Minnesota, St. Paul, MN 55108, USA
[2] Department of Animal Science, University of Minnesota, St. Paul, MN 55108, USA
[3] Department of Agronomy and Plant Genetics, University of Minnesota, St. Paul, MN 55108, USA
* Correspondence: shurs001@umn.edu, chichen@umn.edu

**Supplementary Data**

**Table S1. Sources of Chemicals and Reagents Used in Chemical Analysis, LC-MS Analysis, Structural Confirmation and Quantification.**

| Chemicals and reagents | Vendors |
|---|---|
| 6-Hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid (Trolox), Trichloroacetic acid | Acros Organics (Morris Plains, NJ) |
| Guanidine hydrochloride, 2-hydrazinoquinoline (HQ), Triphenylphosphine (TPP) | Alfa Aesar (Tewksbury, MA) |
| Methanol (HPLC grade) | Avantor performance materials (Radnor, PA) |
| Aldehyde standards*: 2-decenal, 2-hexenal, 2-heptenal, 2,4-heptadienal, octanal, 2-octenal, nonanal, 2-nonenal, 2,4-nonadienal | Bedoukian Research (Danbury, CT) |
| (2,2'-azino-bis (3-ethylbenzothiazoline-6-sulphonic acid) diammonium salt (ABTS) | Chem-Impex International (Wood Dale, IL) |
| Acetonitrile (HPLC-MS grade), Ammonium acetate (HPLC-MS grade), *p*-anisidine, 2,4-dinitrophenylhydrazone (DNPH), Formic acid (HPLC-MS grade), Hydrochloric acid, Isooctane (HPLC grade), Sulfadimethoxine (SDM), Water (HPLC-MS grade) | Fisher Scientific (Houston, TX) |
| Isoflavone standards#: Daidzein, Daidzin, Genistein, Genistin | MedChemExpress (Princeton, NJ) |
| 2-2′-Dipyridyl disulfide (DPDS) | MP Biomedicals, LLC (Irvine, CA) |
| Tripentadecanoin (TG, 15:0, 15:0, 15:0) | Nu-Chek Prep, Inc (Elysian, MN) |
| Dimethyl sulfoxide (DMSO), Ethanol, Ethyl acetate, Folin–Ciocalteu reagent, Sodium carbonate, $\alpha$-tocopherol^, $\gamma$-tocopherol^ | Sigma-Aldrich (St. Louis, MO) |

* Aldehyde standards were dissolved in methanol containing 10 μM acetone-d6 (internal standard) to obtain working standard solutions with the concentration of 0, 5, 12.5, 25, 50, 125, 250 and 500 μM.

# Isoflavone standards were firstly dissolved in DMSO to prepare stock solution (10 mg/mL), and then diluted with methanol containing 1 μM SDM (internal standard) to obtain working standard solutions with the concentration of 0, 0.125, 0.25, 0.5, 1.25, 2.5, 6.25, 12.5, 25 and 62.5 μg/mL.

^ Tocopherol standards were dissolved in methanol containing 5 μg/mL TG (internal standard) and then diluted to obtain working standard solutions with the concentration of 0, 0.05, 0.125, 0.25, 0.5, 1.25, 2.5, 5 and 12.5 μg/mL.

**Table S2. AOAC (2007) Methods for the Proximate Analysis of SSBM and MSBM Samples**

| Proximate analysis components | Procedures |
|---|---|
| Crude protein | AOAC 984.13 |
| Ash | AOAC 942.05 |
| Ether extract | AOAC 920.39 |
| Crude fiber | AOAC 978.10 |
| Moisture | AOAC 934.01 |

**Table S3. LC-MS Data Acquisition Conditions in a 10-minute Run.**

| Target compounds | Column type | Mobile phase | MS detection mode | Capillary and cone voltage | Source and desolvation temperature | Cone and desolvation gas | Collision gas |
|---|---|---|---|---|---|---|---|
| Aldehydes | BEH C18 | A: $H_2O$ containing 0.05% acetic acid (v/v) and 2 mM ammonium acetate<br>B: $H_2O$/ACN = 5:95 (v/v) containing 0.05% acetic acid (v/v) and 2 mM ammonium acetate | Positive | 0.2 kV, 40 V | 120 °C, 350 °C | 50 L/h, 600 L/h ($N_2$) | Argon |
| Tocopherols | BEH C8 | A: $H_2O$ containing 0.02% formic acid (v/v) and 0.1 mM ammonium formate<br>B: Methanol containing 0.02% formic acid (v/v) and 0.1 mM ammonium formate | Positive | 0.5 kV, 40 V | 120 °C, 350 °C | 50 L/h, 600 L/h ($N_2$) | Argon |
| Isoflavones | BEH C18 | A: $H_2O$ containing 0.1% formic acid (v/v)<br>B: Methanol | Positive | 0.2 kV, 40 V | 120 °C, 350 °C | 50 L/h, 600 L/h ($N_2$) | Argon |

**Table S4. Gross Composition of SSBM and MSBM Samples**

| # | Sample type | Year | Crude protein (% DM) | Ash (% DM) | Ether extract (% DM) | Crude fiber (% DM) | Moisture (%) | Water activity |
|---|---|---|---|---|---|---|---|---|
| 1 | SSBM | 2020 | 52.29 | 7.03 | 1.46 | 3.91 | 10.30 | 0.59 |
| 2 | SSBM | 2020 | 51.94 | 6.80 | 1.17 | 4.17 | 10.93 | 0.63 |
| 3 | SSBM | 2020 | 52.19 | 6.69 | 0.96 | 4.00 | 12.23 | 0.68 |
| 4 | SSBM | 2020 | 52.92 | 6.65 | 1.03 | 4.08 | 10.25 | 0.61 |
| 5 | SSBM | 2020 | 52.56 | 6.91 | 0.99 | 3.60 | 10.75 | 0.64 |
| 6 | SSBM | 2020 | 52.35 | 7.07 | 1.55 | 3.68 | 10.52 | 0.63 |
| 7 | SSBM | 2020 | 52.38 | 7.06 | 0.81 | 3.13 | 10.42 | 0.56 |
| 8 | SSBM | 2020 | 53.04 | 7.68 | 0.92 | 3.64 | 11.71 | 0.66 |
| 9 | SSBM | 2020 | 53.42 | 6.79 | 0.59 | 3.72 | 10.70 | 0.62 |
| 10 | SSBM | 2020 | 52.96 | 6.97 | 1.34 | 3.55 | 10.03 | 0.58 |
| 11 | SSBM | 2020 | 50.89 | 7.11 | 1.03 | 3.99 | 9.05 | 0.57 |
| 12 | SSBM | 2020 | 53.50 | 6.77 | 1.25 | 3.41 | 10.43 | 0.61 |
| 13 | SSBM | 2020 | 53.99 | 6.92 | 0.71 | 3.27 | 9.44 | 0.58 |
| 14 | SSBM | 2020 | 51.23 | 6.94 | 1.27 | 4.91 | 10.38 | 0.63 |
| 15 | SSBM | 2020 | 54.24 | 6.97 | 0.55 | 3.27 | 11.25 | 0.66 |
| 16 | SSBM | 2020 | 51.28 | 6.92 | 1.70 | 3.92 | 10.51 | 0.62 |
| 17 | SSBM | 2020 | 51.76 | 6.94 | 0.95 | 4.35 | 10.35 | 0.64 |
| 18 | SSBM | 2020 | 51.12 | 6.93 | 1.13 | 4.13 | 10.87 | 0.65 |
| 19 | SSBM | 2020 | 51.82 | 6.77 | 2.22 | 3.67 | 9.88 | 0.61 |
| 20 | SSBM | 2020 | 52.53 | 8.99 | 1.96 | 4.31 | 10.02 | 0.62 |
| 21 | SSBM | 2020 | 53.10 | 7.39 | 1.55 | 3.76 | 10.79 | 0.64 |
| 22 | SSBM | 2020 | 53.05 | 6.87 | 1.45 | 3.57 | 9.96 | 0.61 |
| 23 | SSBM | 2020 | 53.79 | 7.93 | 2.07 | 3.33 | 10.44 | 0.63 |
| 24 | SSBM | 2020 | 53.85 | 6.95 | 0.65 | 4.02 | 11.11 | 0.65 |
| 25 | SSBM | 2020 | 53.25 | 7.11 | 1.15 | 3.48 | 10.41 | 0.63 |
| 26 | SSBM | 2020 | 51.51 | 6.90 | 1.54 | 4.13 | 8.55 | 0.61 |
| 27 | SSBM | 2020 | 50.95 | 7.09 | 0.80 | 4.31 | 9.08 | 0.63 |
| 28 | SSBM | 2020 | 51.62 | 6.88 | 1.47 | 4.10 | 9.92 | 0.65 |
| 29 | SSBM | 2020 | 52.51 | 7.48 | 2.48 | 4.30 | 10.21 | 0.65 |
| 30 | SSBM | 2020 | 52.06 | 6.68 | 2.66 | 3.55 | 10.03 | 0.63 |
| 31 | SSBM | 2020 | 51.90 | 6.98 | 1.44 | 4.00 | 10.36 | 0.65 |
| 32 | SSBM | 2020 | 52.30 | 6.58 | 2.53 | 3.82 | 10.04 | 0.63 |
| 33 | SSBM | 2020 | 51.45 | 6.89 | 3.60 | 3.39 | 9.39 | 0.63 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 34 | SSBM | 2020 | 51.27 | 6.82 | 2.44 | 4.32 | 9.87 | 0.61 |
| 35 | SSBM | 2020 | 50.55 | 6.86 | 1.31 | 4.59 | 9.90 | 0.62 |
| 36 | SSBM | 2020 | 52.05 | 6.53 | 1.78 | 4.45 | 10.53 | 0.64 |
| 37 | SSBM | 2020 | 49.58 | 7.19 | 1.67 | 5.10 | 10.73 | 0.66 |
| 38 | SSBM | 2020 | 52.37 | 7.10 | 1.35 | 3.71 | 9.88 | 0.61 |
| 39 | SSBM | 2021 | 50.36 | 7.16 | 1.40 | 4.29 | 9.35 | 0.61 |
| 40 | SSBM | 2021 | 54.15 | 7.11 | 2.21 | 3.27 | 9.48 | 0.61 |
| 41 | SSBM | 2021 | 54.49 | 7.12 | 2.28 | 2.94 | 9.30 | 0.61 |
| 42 | SSBM | 2021 | 50.74 | 6.78 | 1.02 | 4.24 | 9.03 | 0.59 |
| 43 | SSBM | 2021 | 52.16 | 6.79 | 0.97 | 3.57 | 9.45 | 0.58 |
| 44 | SSBM | 2021 | 51.03 | 7.31 | 1.62 | 3.72 | 8.78 | 0.59 |
| 45 | SSBM | 2021 | 51.94 | 6.75 | 2.63 | 4.11 | 9.43 | 0.60 |
| 46 | SSBM | 2021 | 52.59 | 6.90 | 1.66 | 4.09 | 9.77 | 0.61 |
| 47 | SSBM | 2021 | 52.80 | 6.69 | 1.59 | 3.51 | 10.60 | 0.64 |
| 48 | SSBM | 2021 | 53.13 | 6.97 | 1.44 | 3.57 | 9.53 | 0.61 |
| 49 | SSBM | 2021 | 51.00 | 6.85 | 3.88 | 4.08 | 9.36 | 0.62 |
| 50 | SSBM | 2021 | 53.22 | 6.58 | 2.43 | 3.49 | 9.47 | 0.61 |
| 51 | SSBM | 2021 | 52.26 | 7.10 | 2.32 | 4.31 | 11.08 | 0.67 |
| 52 | SSBM | 2021 | 52.70 | 6.88 | 1.77 | 3.58 | 8.90 | 0.62 |
| 53 | SSBM | 2021 | 51.37 | 7.26 | 1.88 | 3.27 | 11.81 | 0.66 |
| 54 (HP300)* | SSBM | 2021 | 59.22 | 7.44 | 2.19 | 5.00 | 6.97 | 0.37 |
| 55 | MSBM | 2021 | 46.07 | 6.45 | 5.89 | 6.11 | 5.30 | 0.34 |
| 56 | MSBM | 2021 | 47.54 | 6.07 | 6.86 | 6.68 | 5.24 | 0.40 |
| 57 | MSBM | 2021 | 44.19 | 6.06 | 6.40 | 5.96 | 5.13 | 0.34 |
| 58 | MSBM | 2021 | 48.52 | 6.19 | 6.58 | 9.06 | 3.71 | 0.30 |
| 59 | MSBM | 2021 | 45.35 | 6.17 | 6.76 | 6.16 | 4.92 | 0.32 |
| 60 | MSBM | 2021 | 49.23 | 6.08 | 8.93 | 5.67 | 5.53 | 0.40 |
| 61 | MSBM | 2021 | 48.22 | 6.38 | 6.54 | 5.42 | 4.68 | 0.28 |
| 62 | MSBM | 2021 | 46.07 | 6.39 | 7.41 | 5.96 | 6.83 | 0.45 |

* This sample was produced by treating conventional SSBM with a mixture of enzymes and posttreatment heating.

**Table S5. Protein and Lipid Oxidation of SSBM and MSBM Samples**

| # | Sample type | Year | Carbonyl content (μmol/g protein) | *p*-AV | 2-hexenal | 2,4-heptadienal | 2-heptenal | Octanal | 2-octenal | Nonanal | 2-nonenal | 2,4-nonadienal | 2-decenal | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | ng/g, DM | | | | | | | | | |
| 1 | SSBM | 2020 | 5.5 | 0.05 | 207.1 | 621.0 | 5081.2 | 103.2 | 1343.7 | 120.0 | 101.9 | 13.8 | 3026.4 | 10618.3 |
| 2 | SSBM | 2020 | 6.8 | 0.54 | 252.5 | 832.1 | 5144.4 | 52.9 | 984.0 | 88.5 | 97.0 | 6.0 | 2904.6 | 10362.0 |
| 3 | SSBM | 2020 | 4.2 | 0.41 | 26.2 | 132.6 | 1490.4 | 15.5 | 137.7 | 38.7 | 12.2 | 4.2 | 559.5 | 2417.0 |
| 4 | SSBM | 2020 | 4.8 | 0.67 | 16.9 | 92.4 | 1323.3 | 3.9 | 51.9 | 35.3 | 6.8 | 2.9 | 321.9 | 1855.3 |
| 5 | SSBM | 2020 | 4.0 | 0.54 | 102.5 | 391.4 | 2982.3 | 36.1 | 539.3 | 47.3 | 43.8 | 3.5 | 1582.7 | 5729.0 |
| 6 | SSBM | 2020 | 6.0 | 0.30 | 5.1 | 14.2 | 421.5 | 4.0 | 14.7 | 35.6 | 7.3 | 4.6 | 59.8 | 566.9 |
| 7 | SSBM | 2020 | 5.7 | 0.67 | 18.0 | 71.7 | 1086.2 | 3.6 | 53.5 | 13.2 | 3.6 | 1.7 | 257.4 | 1509.0 |
| 8 | SSBM | 2020 | 4.2 | 0.94 | 13.8 | 44.1 | 956.7 | 0.0 | 10.4 | 51.1 | 5.8 | 4.2 | 129.2 | 1215.1 |
| 9 | SSBM | 2020 | 6.4 | 0.00 | 4.6 | 8.5 | 247.7 | 4.0 | 12.4 | 25.9 | 10.0 | 2.8 | 51.1 | 366.9 |
| 10 | SSBM | 2020 | 4.2 | 0.16 | 3.6 | 7.5 | 194.9 | 1.5 | 17.4 | 14.1 | 2.6 | 1.2 | 23.1 | 265.9 |
| 11 | SSBM | 2020 | 4.6 | 0.52 | 3.4 | 12.4 | 318.1 | 1.1 | 13.4 | 16.1 | 4.9 | 2.8 | 40.8 | 413.0 |
| 12 | SSBM | 2020 | 4.6 | 0.37 | 2.2 | 6.2 | 157.1 | 0.9 | 8.1 | 17.8 | 2.6 | 2.1 | 22.7 | 219.7 |
| 13 | SSBM | 2020 | 5.2 | 0.16 | 6.2 | 26.8 | 569.4 | 4.4 | 26.3 | 38.9 | 5.9 | 5.7 | 83.0 | 766.6 |
| 14 | SSBM | 2020 | 4.8 | 0.13 | 6.1 | 24.5 | 584.6 | 9.4 | 42.4 | 57.2 | 8.3 | 6.8 | 116.3 | 855.6 |
| 15 | SSBM | 2020 | 4.1 | 0.32 | 8.6 | 29.0 | 627.4 | 0.0 | 11.1 | 22.6 | 3.8 | 2.3 | 72.4 | 777.1 |
| 16 | SSBM | 2020 | 9.3 | 0.21 | 3.7 | 16.8 | 419.8 | 3.5 | 23.7 | 37.4 | 7.9 | 5.8 | 63.4 | 581.9 |
| 17 | SSBM | 2020 | 5.8 | 0.25 | 5.8 | 22.2 | 520.6 | 3.4 | 28.1 | 33.3 | 6.8 | 6.7 | 87.3 | 714.1 |
| 18 | SSBM | 2020 | 4.3 | 0.16 | 4.1 | 18.0 | 414.9 | 2.9 | 30.4 | 40.1 | 10.2 | 5.1 | 56.7 | 582.6 |
| 19 | SSBM | 2020 | 4.3 | 0.12 | 3.1 | 22.1 | 466.5 | 0.0 | 9.5 | 25.5 | 5.5 | 2.5 | 45.4 | 580.1 |
| 20 | SSBM | 2020 | 4.9 | 2.13 | 69.4 | 389.1 | 3475.6 | 5.3 | 166.6 | 47.5 | 15.6 | 1.8 | 1129.7 | 5300.5 |
| 21 | SSBM | 2020 | 6.2 | 0.79 | 24.5 | 57.0 | 1101.4 | 0.0 | 13.0 | 48.9 | 7.5 | 2.7 | 183.5 | 1438.5 |
| 22 | SSBM | 2020 | 5.0 | 0.59 | 3.1 | 12.8 | 303.0 | 3.5 | 18.3 | 46.9 | 10.2 | 6.8 | 50.9 | 455.5 |
| 23 | SSBM | 2020 | 6.6 | 0.60 | 10.9 | 31.4 | 511.6 | 4.4 | 40.0 | 23.5 | 11.2 | 20.1 | 81.0 | 734.2 |
| 24 | SSBM | 2020 | 6.3 | 0.00 | 4.6 | 12.9 | 334.7 | 3.3 | 18.1 | 35.0 | 9.9 | 5.5 | 49.6 | 473.6 |
| 25 | SSBM | 2020 | 3.1 | 0.15 | 3.1 | 12.1 | 348.0 | 4.5 | 20.4 | 49.4 | 7.2 | 5.6 | 68.8 | 519.1 |
| 26 | SSBM | 2020 | 4.2 | 0.28 | 7.0 | 26.4 | 650.1 | 5.0 | 36.9 | 44.4 | 11.4 | 7.1 | 120.7 | 909.0 |
| 27 | SSBM | 2020 | 3.6 | 0.08 | 16.0 | 38.8 | 766.5 | 3.5 | 30.7 | 37.0 | 9.2 | 10.7 | 83.5 | 996.0 |
| 28 | SSBM | 2020 | 4.6 | 0.18 | 12.7 | 20.3 | 472.2 | 7.0 | 28.3 | 107.9 | 17.0 | 17.3 | 69.5 | 752.3 |
| 29 | SSBM | 2020 | 5.3 | 0.96 | 170.9 | 630.6 | 5326.0 | 8.3 | 252.4 | 50.1 | 21.5 | 4.1 | 1428.6 | 7892.4 |
| 30 | SSBM | 2020 | 6.2 | 0.14 | 0.6 | 3.1 | 66.0 | 11.1 | 9.7 | 71.8 | 9.9 | 2.1 | 278.9 | 453.2 |
| 31 | SSBM | 2020 | 5.6 | 0.31 | 3.2 | 12.6 | 348.8 | 0.7 | 19.5 | 36.3 | 7.9 | 5.9 | 55.8 | 490.8 |
| 32 | SSBM | 2020 | 3.0 | 0.31 | 4.2 | 21.6 | 285.4 | 2.7 | 19.3 | 107.8 | 13.5 | 8.4 | 46.7 | 509.6 |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 33 | SSBM | 2020 | 5.2 | 0.88 | 3.4 | 14.6 | 366.1 | 0.0 | 13.7 | 60.9 | 17.9 | 4.8 | 43.3 | 524.7 |
| 34 | SSBM | 2020 | 5.9 | 0.60 | 13.1 | 26.3 | 799.6 | 0.0 | 21.7 | 61.3 | 6.4 | 4.4 | 90.3 | 1023.1 |
| 35 | SSBM | 2020 | 3.8 | 0.23 | 14.2 | 50.0 | 1137.3 | 0.0 | 26.6 | 60.7 | 11.6 | 5.4 | 123.8 | 1429.6 |
| 36 | SSBM | 2020 | 4.1 | 0.56 | 4.4 | 37.8 | 820.4 | 2.2 | 19.1 | 57.0 | 7.0 | 9.6 | 84.8 | 1042.3 |
| 37 | SSBM | 2020 | 4.6 | 0.05 | 16.2 | 60.3 | 1132.9 | 0.0 | 2.1 | 45.6 | 3.1 | 1.0 | 160.9 | 1422.1 |
| 38 | SSBM | 2020 | 3.6 | 0.83 | 5.9 | 24.7 | 702.1 | 0.3 | 28.0 | 74.2 | 6.5 | 3.7 | 110.2 | 955.6 |
| 39 | SSBM | 2021 | 5.6 | 0.17 | 71.4 | 516.1 | 1291.8 | 0.0 | 130.6 | 0 | 0.6 | 7.0 | 250.4 | 2267.9 |
| 40 | SSBM | 2021 | 8.8 | 0.36 | 16.0 | 239.8 | 1299.1 | 0.0 | 70.3 | 0 | 2.4 | 0.3 | 198.8 | 1826.7 |
| 41 | SSBM | 2021 | 6.4 | 0.00 | 13.6 | 225.8 | 1351.3 | 0.0 | 57.0 | 0 | 2.6 | 0.0 | 245.0 | 1895.5 |
| 42 | SSBM | 2021 | 7.1 | 0.21 | 31.0 | 636.5 | 1426.0 | 0.0 | 260.9 | 0 | 11.7 | 4.1 | 835.2 | 3205.4 |
| 43 | SSBM | 2021 | 6.4 | 0.64 | 19.8 | 482.6 | 1108.0 | 0.0 | 122.1 | 0 | 1.7 | 2.5 | 250.8 | 1987.4 |
| 44 | SSBM | 2021 | 7.8 | 0.38 | 38.6 | 854.1 | 1720.3 | 0.0 | 238.5 | 0 | 7.8 | 6.3 | 593.0 | 3458.7 |
| 45 | SSBM | 2021 | 6.6 | 0.00 | 23.8 | 974.2 | 2431.8 | 0.0 | 212.6 | 0 | 15.8 | 5.8 | 1047.3 | 4711.3 |
| 46 | SSBM | 2021 | 7.7 | 0.58 | 53.8 | 863.6 | 1745.0 | 0.0 | 241.1 | 0 | 5.9 | 5.0 | 470.8 | 3385.2 |
| 47 | SSBM | 2021 | 7.2 | 0.94 | 30.2 | 725.5 | 1830.1 | 0.0 | 323.2 | 0 | 17.2 | 6.7 | 933.3 | 3866.1 |
| 48 | SSBM | 2021 | 4.5 | 0.28 | 10.9 | 228.0 | 990.4 | 43.0 | 145.0 | 0 | 141.8 | 2.4 | 1876.1 | 3437.7 |
| 49 | SSBM | 2021 | 9.4 | 0.98 | 18.8 | 459.6 | 2733.0 | 0.0 | 378.1 | 0 | 26.8 | 16.7 | 1076.2 | 4709.2 |
| 50 | SSBM | 2021 | 5.9 | 0.69 | 3.5 | 56.3 | 788.0 | 1.2 | 140.7 | 0 | 15.4 | 7.8 | 181.7 | 1194.6 |
| 51 | SSBM | 2021 | 4.4 | 0.53 | 12.3 | 242.1 | 1386.8 | 0.0 | 113.8 | 0 | 4.5 | 7.1 | 249.4 | 2016.0 |
| 52 | SSBM | 2021 | 7.8 | 0.02 | 6.8 | 89.3 | 1050.2 | 0.0 | 215.2 | 0 | 5.4 | 8.7 | 274.7 | 1650.4 |
| 53 | SSBM | 2021 | 6.8 | 0.93 | 4.0 | 32.0 | 426.7 | 11.1 | 40.0 | 39.3 | 2.0 | 4.3 | 133.8 | 693.3 |
| 54 (HP300) * | SSBM | 2021 | 9.3 | 2.29 | 75.8 | 118.2 | 1779.2 | 12.1 | 148.6 | 21.8 | 11.2 | 3.5 | 423.6 | 2594.0 |
| 55 | MSBM | 2021 | 7.7 | 0.79 | 9.8 | 33.7 | 309.4 | 24.7 | 52.8 | 96.4 | 2.8 | 4.6 | 105.6 | 639.9 |
| 56 | MSBM | 2021 | 10.9 | 1.58 | 29.1 | 88.4 | 759.0 | 25.7 | 102.3 | 106.2 | 6.8 | 6.7 | 246.4 | 1370.6 |
| 57 | MSBM | 2021 | 11.4 | 0.88 | 26.4 | 88.1 | 1780.8 | 27.8 | 142.4 | 87.1 | 22.0 | 7.2 | 457.5 | 2639.2 |
| 58 | MSBM | 2021 | 14.1 | 0.49 | 629.1 | 1791.7 | 17492.8 | 161.4 | 2364.8 | 215.4 | 227.8 | 21.2 | 9671.3 | 32575.6 |
| 59 | MSBM | 2021 | 6.4 | 1.31 | 8.9 | 42.2 | 619.1 | 14.5 | 50.3 | 57.8 | 4.2 | 6.2 | 205.3 | 1008.5 |
| 60 | MSBM | 2021 | 5.2 | 1.73 | 35.4 | 122.4 | 1241.7 | 30.0 | 159.9 | 97.0 | 8.2 | 6.7 | 360.8 | 2062.1 |
| 61 | MSBM | 2021 | 8.3 | 1.49 | 10.3 | 52.9 | 174.1 | 15.4 | 27.4 | 64.0 | 4.2 | 12.4 | 35.8 | 396.5 |
| 62 | MSBM | 2021 | 9.7 | 1.71 | 160.9 | 456.6 | 5048.6 | 120.9 | 1009.7 | 172.8 | 59.6 | 25.8 | 1884.0 | 8938.8 |

* This sample was produced by treating conventional SSBM with a mixture of enzymes and posttreatment heating.

**Table S6. Antioxidants of SSBM and MSBM Samples**

| # | Sample type | Year | TEAC | Total phenolic content (mg/g caffeic acid equivalent DM) | α-tocopherol | γ-tocopherol | Daidzin | Genistin | Daidzein | Genistein |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | μg/g DM | | | | | |
| 1 | SSBM | 2020 | 24.6 | 1.05 | 0.008 | 6.1 | 397.8 | 1527.6 | 42.3 | 42.3 |
| 2 | SSBM | 2020 | 25.0 | 1.34 | 0.015 | 5.7 | 577.1 | 2153.4 | 42.7 | 35.9 |
| 3 | SSBM | 2020 | 25.0 | 1.34 | 0.003 | 5.9 | 451.2 | 1488.0 | 14.8 | 17.1 |
| 4 | SSBM | 2020 | 25.4 | 1.14 | 0.008 | 5.6 | 460.2 | 1551.0 | 21.2 | 20.1 |
| 5 | SSBM | 2020 | 24.3 | 1.32 | 0.001 | 1.7 | 384.3 | 1166.4 | 15.7 | 15.7 |
| 6 | SSBM | 2020 | 25.9 | 1.24 | 0.001 | 5.9 | 516.3 | 1865.2 | 35.8 | 34.6 |
| 7 | SSBM | 2020 | 24.6 | 1.14 | 0.010 | 1.6 | 428.7 | 1444.5 | 20.1 | 20.1 |
| 8 | SSBM | 2020 | 25.5 | 1.25 | 0.017 | 4.4 | 427.0 | 1500.7 | 61.2 | 48.7 |
| 9 | SSBM | 2020 | 25.1 | 1.11 | 0.015 | 7.8 | 486.0 | 1753.6 | 34.7 | 33.6 |
| 10 | SSBM | 2020 | 25.3 | 1.16 | 0.000 | 7.3 | 436.8 | 1480.5 | 16.7 | 17.8 |
| 11 | SSBM | 2020 | 25.7 | 1.32 | 0.001 | 6.3 | 469.5 | 1655.9 | 20.9 | 22.0 |
| 12 | SSBM | 2020 | 24.4 | 1.37 | 0.004 | 7.0 | 470.0 | 1558.6 | 24.6 | 24.6 |
| 13 | SSBM | 2020 | 25.0 | 1.27 | 0.002 | 2.4 | 491.4 | 1866.2 | 23.2 | 27.6 |
| 14 | SSBM | 2020 | 25.0 | 1.23 | 0.003 | 6.7 | 421.8 | 1418.2 | 17.9 | 17.9 |
| 15 | SSBM | 2020 | 24.8 | 1.12 | 0.006 | 4.1 | 442.8 | 1542.5 | 45.1 | 39.4 |
| 16 | SSBM | 2020 | 25.0 | 1.09 | 0.002 | 7.8 | 539.7 | 1891.8 | 31.3 | 30.2 |
| 17 | SSBM | 2020 | 24.6 | 1.17 | 0.005 | 8.3 | 441.7 | 1459.0 | 15.6 | 16.7 |
| 18 | SSBM | 2020 | 25.2 | 1.29 | 0.003 | 6.7 | 535.2 | 1807.5 | 26.9 | 25.8 |
| 19 | SSBM | 2020 | 25.3 | 1.23 | 0.004 | 13.1 | 512.6 | 1643.4 | 24.4 | 23.3 |
| 20 | SSBM | 2020 | 25.3 | 1.22 | 0.004 | 8.9 | 445.7 | 1469.2 | 43.3 | 35.6 |
| 21 | SSBM | 2020 | 25.5 | 1.19 | 0.007 | 8.8 | 483.1 | 1705.0 | 41.5 | 34.7 |
| 22 | SSBM | 2020 | 24.6 | 1.36 | 0.007 | 10.2 | 459.8 | 1542.6 | 22.2 | 22.2 |
| 23 | SSBM | 2020 | 25.2 | 1.17 | 0.001 | 8.5 | 413.1 | 1545.3 | 40.2 | 38.0 |
| 24 | SSBM | 2020 | 25.5 | 1.15 | 0.011 | 9.3 | 495.0 | 1825.9 | 33.7 | 31.5 |
| 25 | SSBM | 2020 | 25.0 | 1.03 | 0.012 | 7.3 | 456.5 | 1593.9 | 26.8 | 24.6 |
| 26 | SSBM | 2020 | 24.2 | 1.08 | 0.003 | 5.7 | 444.0 | 1515.6 | 23.0 | 21.9 |
| 27 | SSBM | 2020 | 24.0 | 1.08 | 0.009 | 1.8 | 414.7 | 1377.0 | 18.7 | 16.5 |
| 28 | SSBM | 2020 | 24.5 | 1.20 | 0.002 | 25.9 | 439.6 | 1452.0 | 12.2 | 13.3 |
| 29 | SSBM | 2020 | 24.5 | 1.06 | 0.001 | 1.6 | 291.8 | 1114.8 | 21.2 | 20.0 |
| 30 | SSBM | 2020 | 25.2 | 0.72 | 0.059 | 3.1 | 619.1 | 2198.5 | 30.0 | 34.5 |
| 31 | SSBM | 2020 | 24.9 | 1.13 | 0.012 | 8.0 | 387.1 | 1327.5 | 12.3 | 13.4 |
| 32 | SSBM | 2020 | 24.8 | 1.17 | 0.012 | 9.1 | 499.1 | 1788.6 | 34.5 | 30.0 |
| 33 | SSBM | 2020 | 25.2 | 1.16 | 0.004 | 20.0 | 512.1 | 1842.0 | 35.3 | 32.0 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 34 | SSBM | 2020 | 24.9 | 1.24 | 0.001 | 6.6 | 482.6 | 1690.9 | 15.5 | 17.8 |
| 35 | SSBM | 2020 | 25.1 | 0.98 | 0.007 | 4.5 | 581.6 | 2105.4 | 23.3 | 25.5 |
| 36 | SSBM | 2020 | 25.1 | 1.12 | 0.003 | 7.0 | 477.3 | 1542.4 | 20.1 | 19.0 |
| 37 | SSBM | 2020 | 25.7 | 1.10 | 0.002 | 5.8 | 506.3 | 1802.4 | 25.8 | 23.5 |
| 38 | SSBM | 2020 | 24.7 | 1.10 | 0.001 | 5.5 | 436.1 | 1495.8 | 21.1 | 18.9 |
| 39 | SSBM | 2021 | 22.6 | 0.96 | 0.011 | 3.4 | 453.4 | 1533.4 | 23.2 | 19.9 |
| 40 | SSBM | 2021 | 23.9 | 0.64 | 0.012 | 4.4 | 449.6 | 1472.6 | 32.0 | 26.5 |
| 41 | SSBM | 2021 | 24.1 | 1.01 | 0.001 | 4.3 | 458.7 | 1637.3 | 39.7 | 34.2 |
| 42 | SSBM | 2021 | 25.9 | 1.22 | 0.002 | 5.6 | 536.4 | 1931.4 | 35.2 | 29.7 |
| 43 | SSBM | 2021 | 27.2 | 1.33 | 0.001 | 4.1 | 522.4 | 1782.4 | 37.5 | 30.9 |
| 44 | SSBM | 2021 | 26.9 | 1.48 | 0.013 | 8.3 | 535.0 | 1839.5 | 36.2 | 31.8 |
| 45 | SSBM | 2021 | 26.2 | 1.23 | 0.007 | 17.8 | 403.0 | 1330.5 | 33.1 | 27.6 |
| 46 | SSBM | 2021 | 25.0 | 1.07 | 0.034 | 10.5 | 410.1 | 1546.0 | 27.7 | 26.6 |
| 47 | SSBM | 2021 | 24.7 | 1.07 | 0.005 | 7.9 | 415.0 | 1550.3 | 36.9 | 35.8 |
| 48 | SSBM | 2021 | 22.3 | 0.96 | 0.004 | 3.8 | 392.4 | 1404.9 | 22.1 | 23.2 |
| 49 | SSBM | 2021 | 24.6 | 1.15 | 0.012 | 5.2 | 417.0 | 1523.6 | 15.4 | 27.6 |
| 50 | SSBM | 2021 | 26.0 | 1.24 | 0.010 | 16.8 | 417.5 | 1602.8 | 34.2 | 29.8 |
| 51 | SSBM | 2021 | 26.4 | 1.11 | 0.009 | 8.6 | 376.7 | 1368.6 | 30.4 | 23.6 |
| 52 | SSBM | 2021 | 25.6 | 1.22 | 0.002 | 1.0 | 355.7 | 1182.2 | 29.6 | 13.2 |
| 53 | SSBM | 2021 | 23.7 | 1.31 | 0.003 | 9.8 | 538.6 | 1680.5 | 40.8 | 36.3 |
| 54 (HP300) * | SSBM | 2021 | 26.9 | 0.97 | 0.011 | 6.9 | 402.0 | 1384.5 | 113.9 | 66.6 |
| 55 | MSBM | 2021 | 23.3 | 0.68 | 0.011 | 9.7 | 264.0 | 861.7 | 21.1 | 31.7 |
| 56 | MSBM | 2021 | 22.6 | 0.56 | 0.014 | 23.1 | 395.7 | 1240.0 | 30.6 | 34.8 |
| 57 | MSBM | 2021 | 24.2 | 0.93 | 0.137 | 21.8 | 375.3 | 1222.7 | 56.9 | 56.9 |
| 58 | MSBM | 2021 | 23.8 | 0.54 | 0.560 | 16.2 | 300.1 | 1082.1 | 48.8 | 43.6 |
| 59 | MSBM | 2021 | 23.0 | 0.95 | 0.018 | 15.1 | 253.5 | 726.8 | 16.8 | 18.9 |
| 60 | MSBM | 2021 | 23.3 | 0.91 | 0.004 | 8.7 | 347.2 | 899.8 | 23.3 | 23.3 |
| 61 | MSBM | 2021 | 24.9 | 1.20 | 0.046 | 9.0 | 411.2 | 1377.5 | 35.7 | 39.9 |
| 62 | MSBM | 2021 | 23.8 | 1.12 | 0.018 | 10.3 | 322.0 | 1151.7 | 48.3 | 50.4 |

* This sample was produced by treating conventional SSBM with a mixture of enzymes and posttreatment heating.

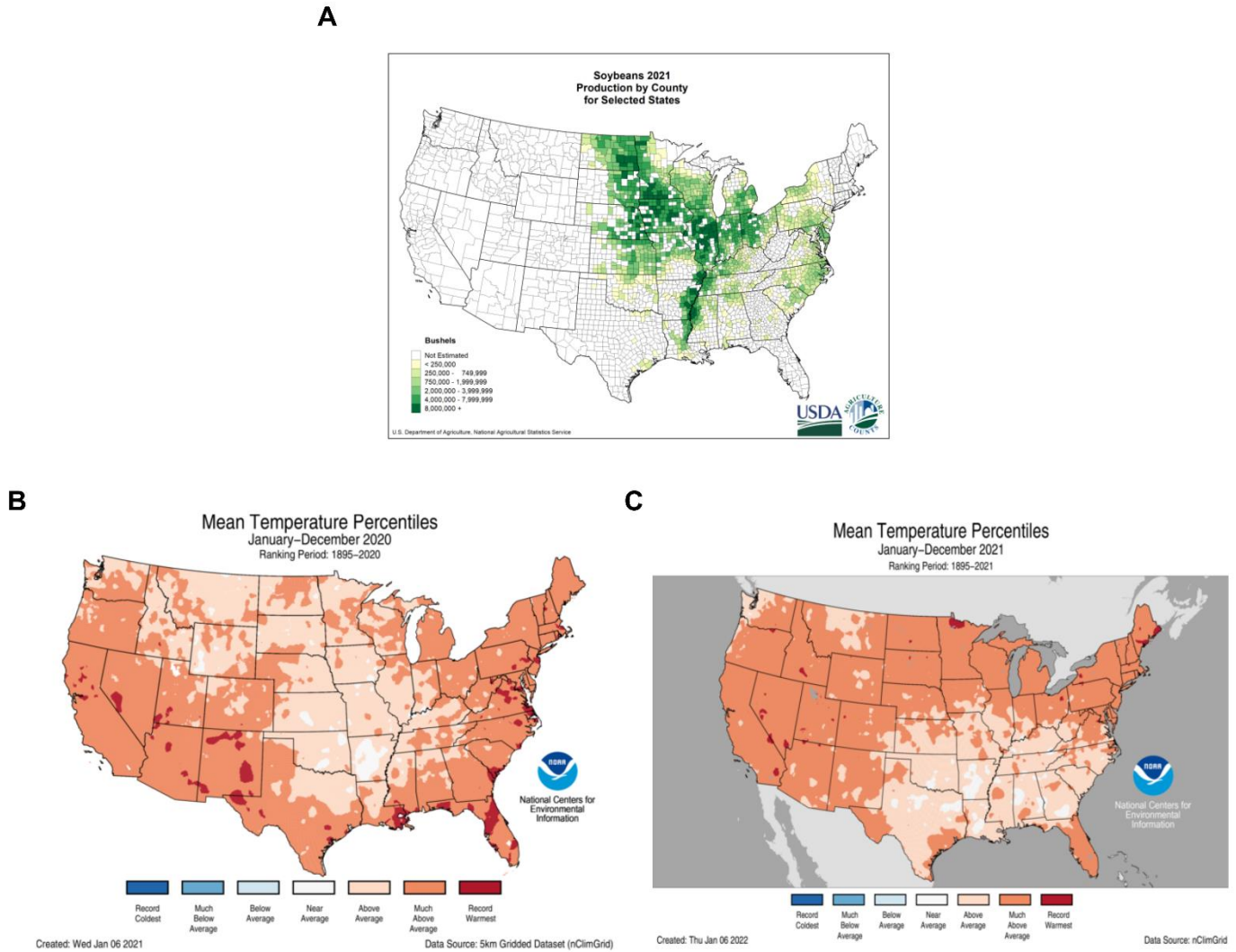


**Figure S1.** Soybean Production Map and Mean Temperature in the United States. **(A**) USDA map of 2021 soybeans production (copied from https://www.nass.usda.gov/Charts_and_Maps/Crops_County/sb-pr.php), **(B)** NOAA map of mean temperature percentiles in 2020 (copied from https://www.ncei.noaa.gov/news/national-climate-202012), **(C)** NOAA map of mean temperature percentiles in 2021 (copied from https://www.ncei.noaa.gov/news/national-climate-202112).