Supporting information

What is the limit of vertical farming productivity?

Sebastian Eichelsbacher[1], Claudia R. Luksch[1], Gerd Patrick Bienert[2], Thomas D. Alcock[2], Kathy Steppe[3], Leo F.M. Marcelis[4], Francesco Orsini[5], Eva Rosenqvist[6], Hans Lambers[7], Erik Runkle[8], Tracy Lawson[9], Senthold Asseng[1,*]

[1] Technical University of Munich, TUM School of Life Sciences, Department of Life Science Engineering, Digital Agriculture, HEF World Agricultural Systems Center, Freising, Germany
[2] Technical University of Munich, TUM School of Life Sciences, Department of Molecular Life Sciences, Crop Physiology, Freising, Germany
[3] Ghent University, Faculty of Bioscience Engineering, Laboratory of Plant Ecology, Ghent, Belgium
[4] Wageningen University, Horticulture and Product Physiology, Wageningen, Netherlands
[5] University of Bologna, Department of Agricultural Sciences, Bologna, Italy
[6] University of Copenhagen, Department of Plant and Environmental Sciences, Taastrup, Denmark
[7] The University of Western Australia, School of Biological Sciences and Institute of Agriculture, Perth, WA009, Australia
[8] Michigan State University, Department of Horticulture, East Lansing, MI, United States
[9] University of Essex, School of Life Sciences, Plant Physiology, Colchester, England

*Correspondence: senthold.asseng@tum.de (S. Asseng)

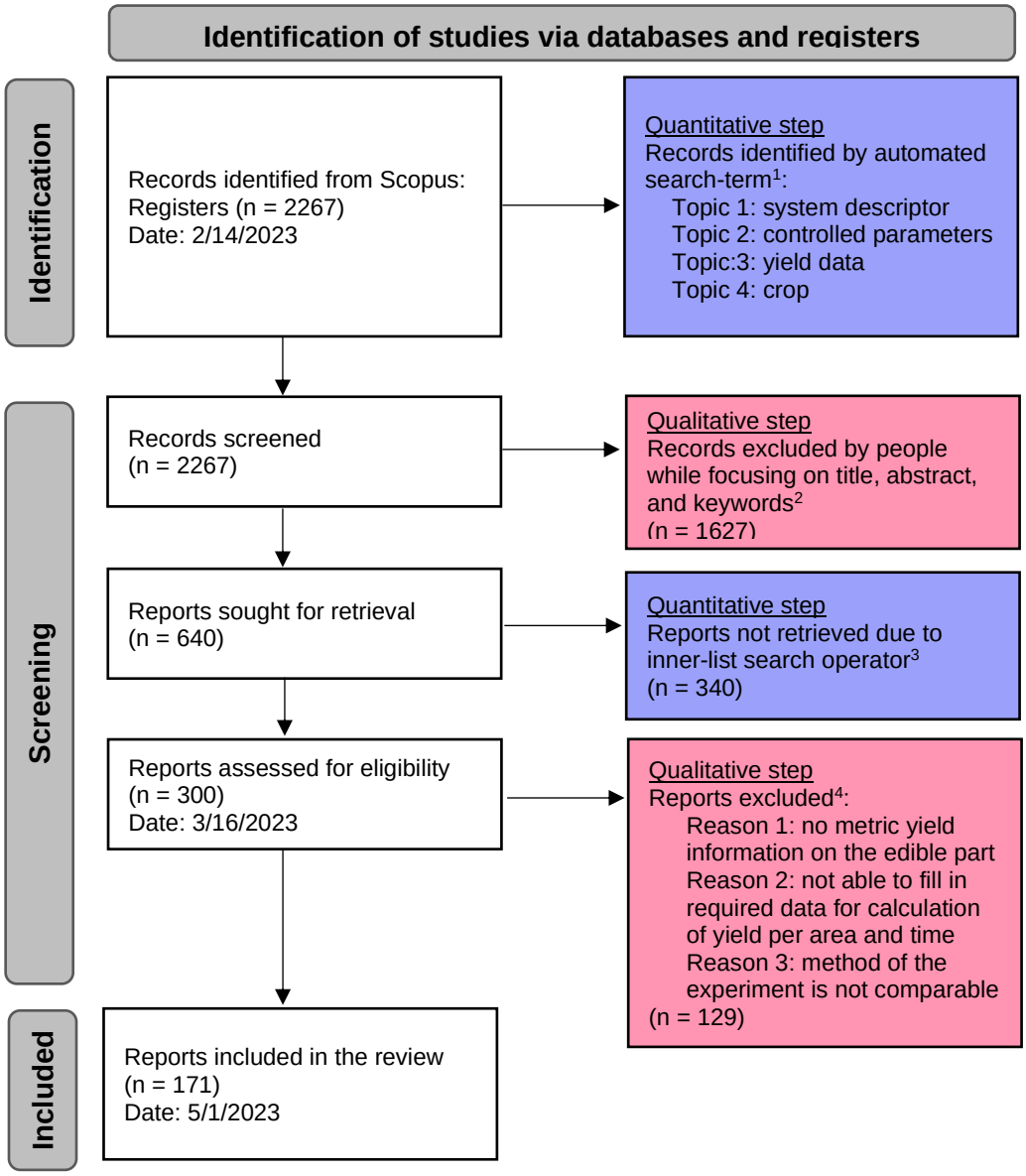

Figure S1 Adapted Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram inspired by Page et al. (2021). We utilized a multi-reference meta-analysis for crop experiments in controlled environments. We employed a five-step process oriented on PRISMA. Initially, we performed a quantitative search on Scopus using four key topics describing vertical farming (VF), controlled factors, and metric yield data for various crops. Subsequently, we performed a qualitative assessment, screening 2267 titles and abstracts. We omitted references that did not investigate commercial food crops, such as pharmaceutical or medical plants, leaving 640 references. We refined the selection in the third step by utilizing a quantitative exclusion operator, removing studies from the greenhouse, or employing sunlight. Further exclusions encompassed experiments on fungi, viruses, stress, and deficiencies. Additionally, experiments on microgreens or basil, as well as on seedling production were omitted as they were deemed less relevant to human nutrition. The remaining 300 references underwent a detailed qualitative analysis in the fourth step, with data extraction, when possible, performed in the fifth step. Data presented in the figures were extracted using PlotDigitizer (PlotDigitizer: Version 3.1.5 2023).

[1]Search-term:TITLE-ABS-KEY (("climate chamb*" OR "growth chamb*" OR "controlled environm*" OR "indoor farm*" OR "indoor agri*" OR "vertical farm*" OR "vertical agri*" OR "plant fact*" OR "controlled plant production syst*" OR "bioregenerative life support

syst*") AND ("light*" OR "temp*" OR "CO2*" OR "humid*") AND ("dry weight*" OR "fresh weight*" OR "dry mass*" OR "fresh mass*" OR "*grams*" OR "yield*") AND ("plant*" OR "crop*" OR "harvest*")) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (SRCTYPE , "j") OR LIMIT-TO (SRCTYPE , "p"))

[2]Focus on constraints such as crop type (exclude pharmaceutical or medical crops, microgreens or herbs, flowers or Arabidopsis) or production system (exclude greenhouse, combined production of greenhouse and climate chamber)

[3]Learnings based on the qualitative step before. Exclude experiments that primarily address plant stress, crop deficiencies, greenhouse cultivation, fungus or virus analysis. Search-term: ( ) AND (( ) AND NOT (TITLE-ABS-KEY ("stress" OR "deficienc*" OR "microgreen*" OR "basil*" OR "fung*" OR "virus" OR "infection*" OR "greenhous*" OR "glasshous*" OR "field*" OR "sunlight*" OR "seedling*" OR "sprout*" OR "medic*" OR "pharma*")))

[4]Examine the textual content of the reports

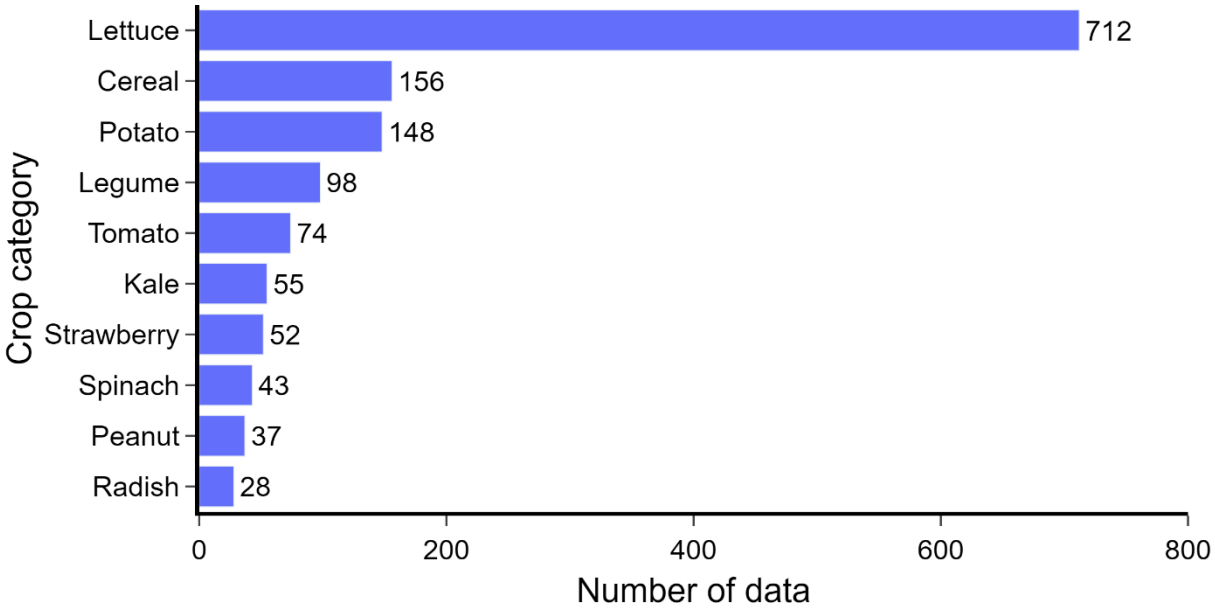

Figure S2 Number of data sets used in the meta-analysis for various crop categories.

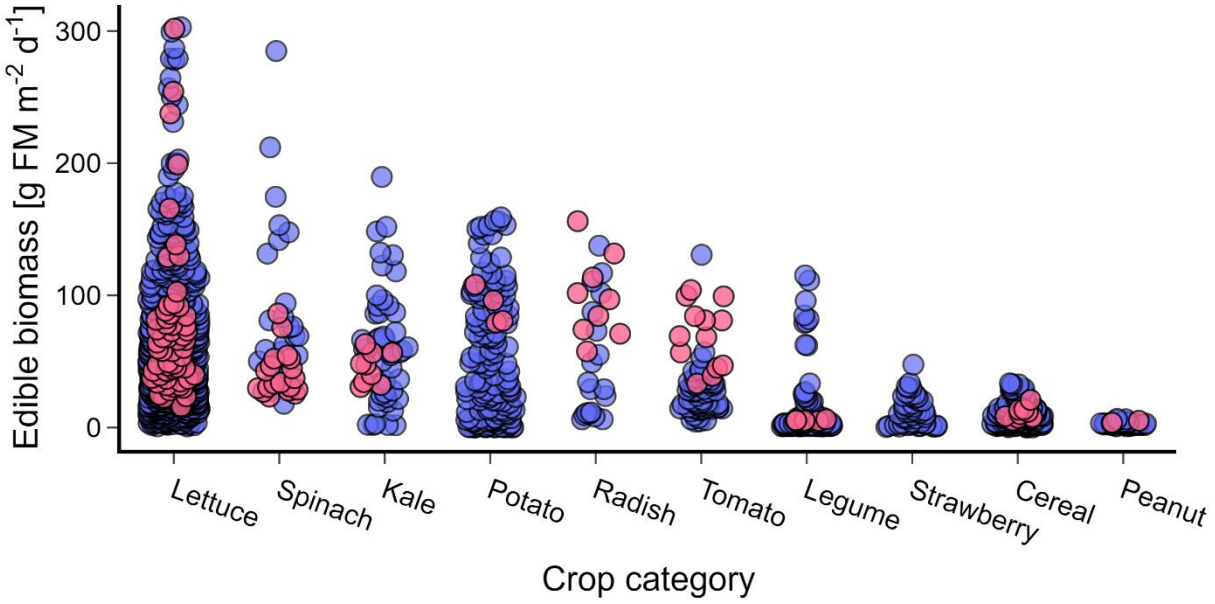

Figure S3 Productivity (edible biomass on a fresh mass basis per area and time) obtained from fully controlled-environment experiments sourced from literature cited in the main text. Crop categories are primarily organized by taxonomical relationships, but the origin of the edible biomass is also considered, with some individual plant species directly delineated. Data are arranged in order of descending peak value from left to right. The pink symbols represent data where canopy density is clearly reported, while blue symbols indicate missing information on precise pot spacing or border effects. The darkness of the symbols reflects data density. Significant variation in productivity, both within and among crops, is attributed to large differences in growth conditions, such as light intensity, photoperiod, and temperature.

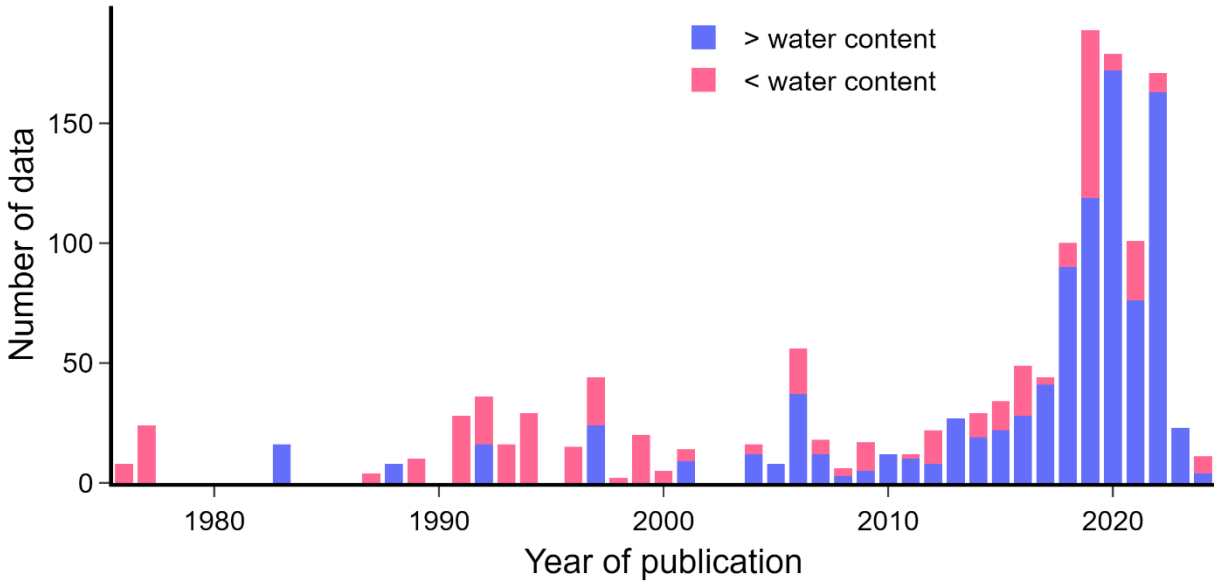

Figure S4 Year of publication of analyzed studies. Blue indicates crops with high moisture (> 80% water content) in the edible biomass at the harvest stage, such as lettuce. In comparison, pink represents crops with low moisture (≤ 80% water content) in the edible biomass at the harvest stage, such as cereals.

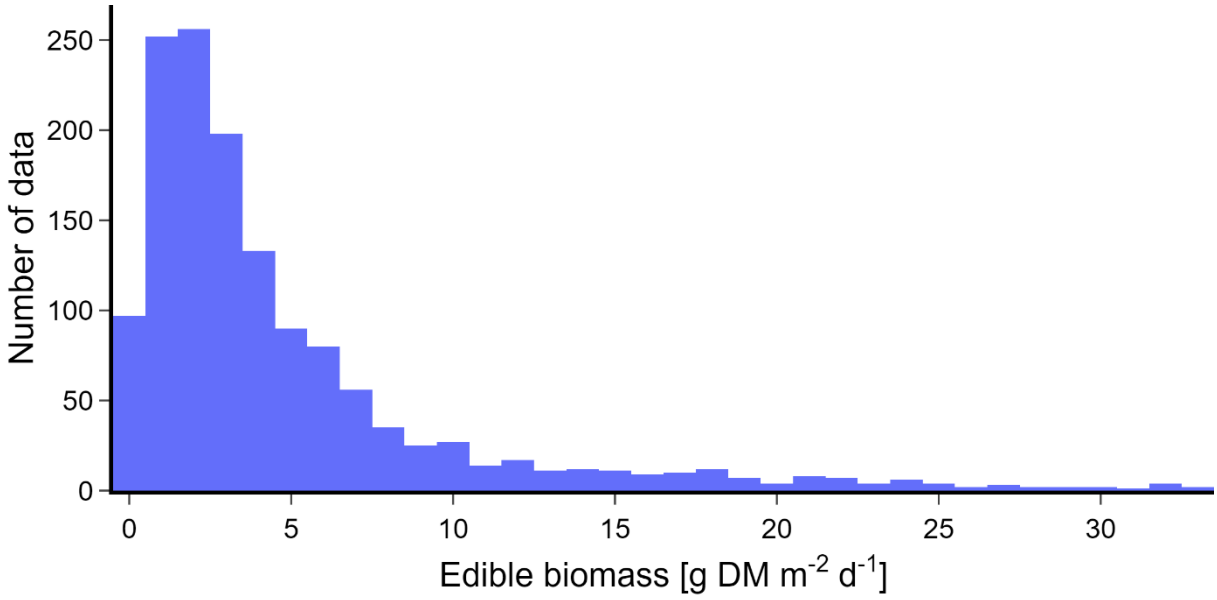

Figure S5 Distribution of productivity across all crops (edible biomass on a dry mass basis per area and time) obtained from fully controlled-environment experiments sourced from the literature. The distribution is right-skewed. Note that a limited number of data sets describe very high productivity.

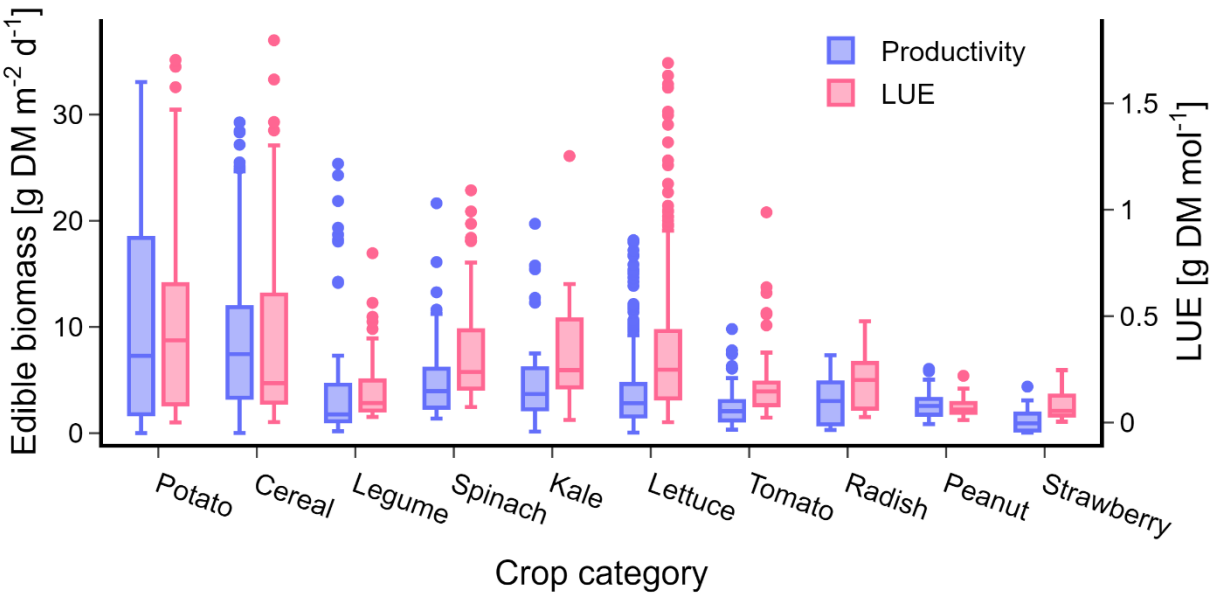

Figure S6 Distribution of productivity (edible biomass on a dry mass basis per area and time) and light-use efficiency (LUE) obtained from fully controlled-environment experiments sourced from the literature included in our harmonized dataset. The box represents the interquartile range, with the median marked by a horizontal line. Whiskers extend to the minimum and maximum values within 1.5 times the interquartile range, and outliers are plotted as individual points. Blue boxplots show productivity, while pink boxplots illustrate LUE for each crop category. The y-axis for LUE is on the right side of the plot.

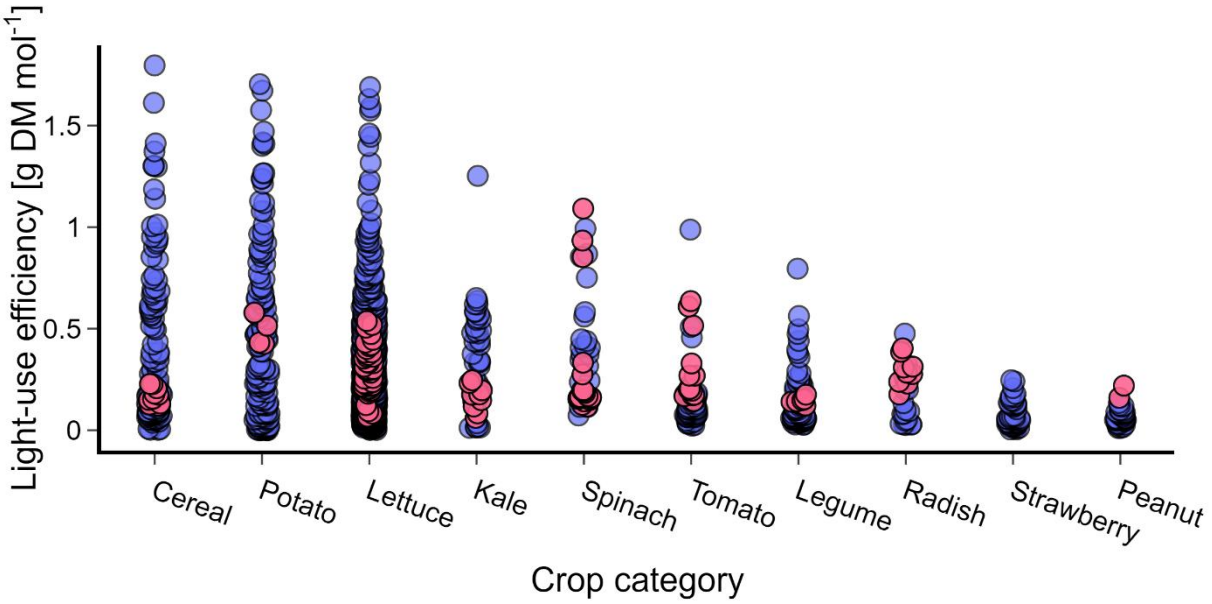

Figure S7 Light-use efficiency (LUE) for edible dry mass obtained from fully controlled-environment experiments. LUE is only presented when photoperiod and light intensity are provided. Data are arranged in order of descending peak value from left to right. The pink symbols represent data where canopy density is clearly reported, while blue symbols indicate missing information on precise pot spacing or border effects. The darkness of the symbols reflects data density.

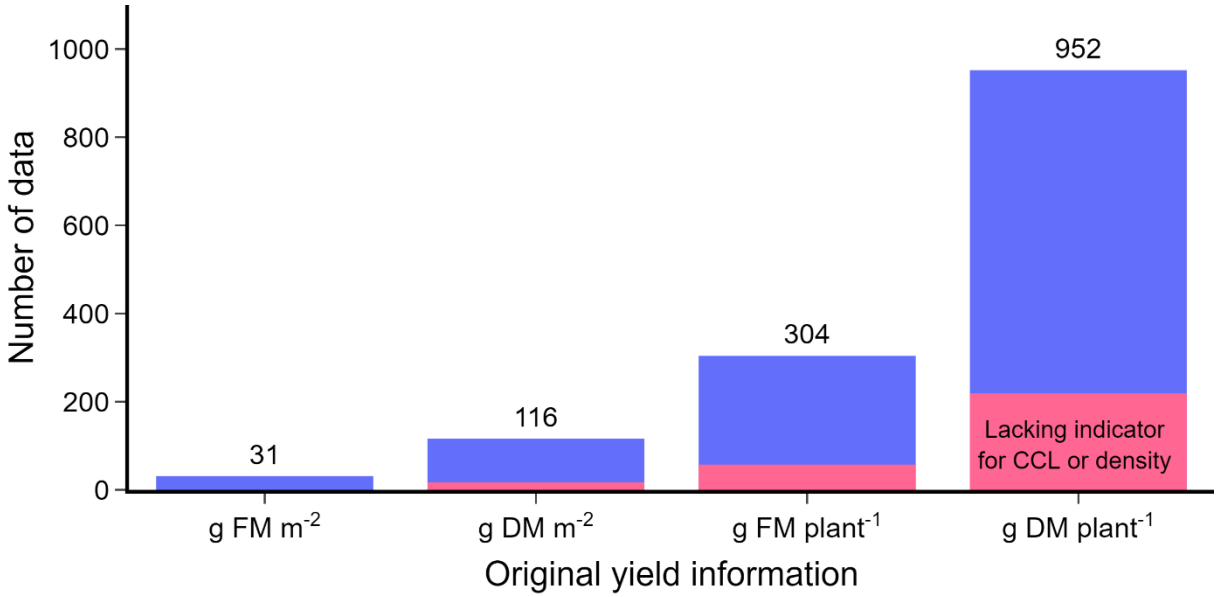

Figure S8 Original yield units used in meta-analysis to calculate edible dry mass per unit area and time for data obtained from fully controlled-environment experiments sourced from the literature. Pink shows the amount of data, which does not have a single indicator for crop cycle length (CCL) or planting density. In these cases, generalized standard factors were used.

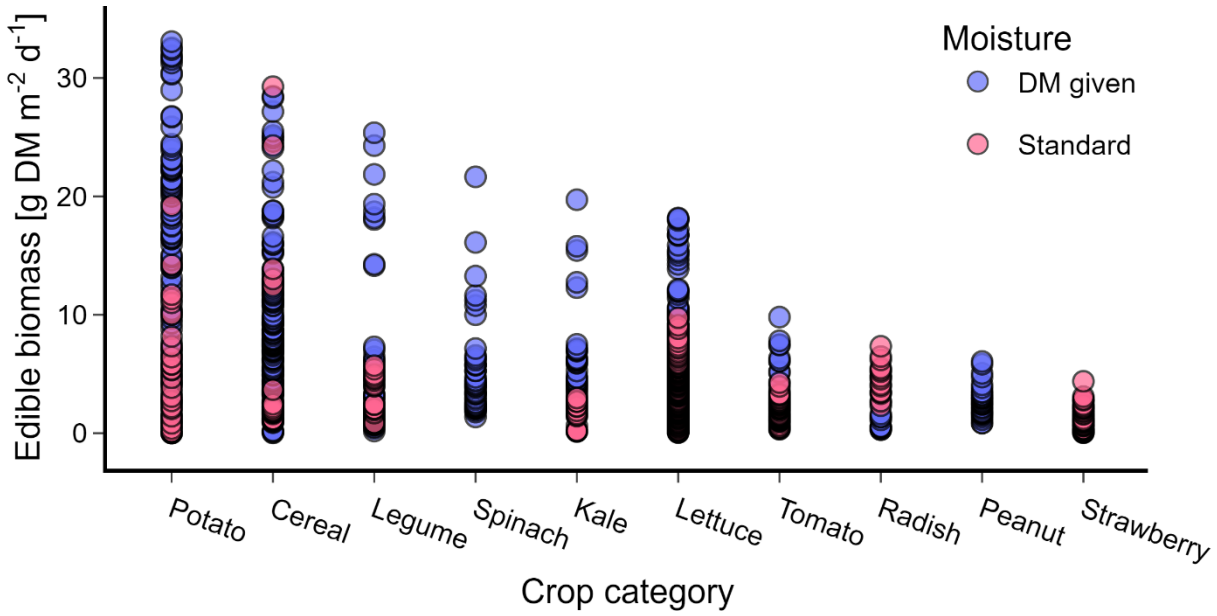

Figure S9 Correlation between calculated productivity (edible biomass on a dry mass basis per area and time) based on reported dry mass values (blue) and those derived from standard moisture parameter (pink). Data obtained from fully controlled-environment experiments sourced from the literature.

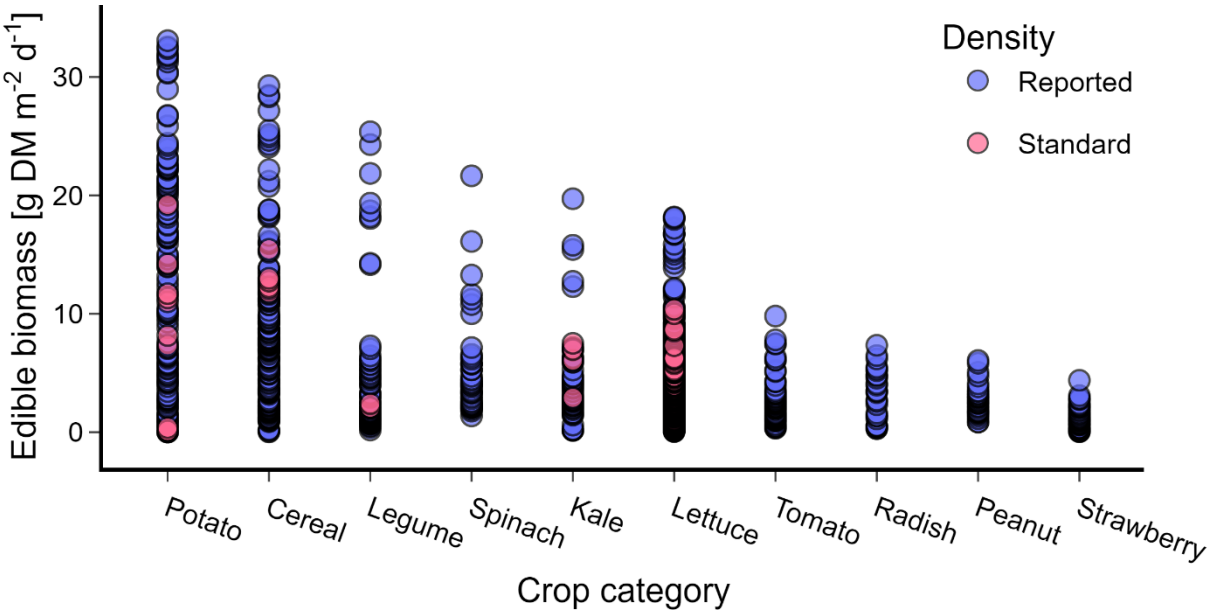

Figure S10 Correlation between calculated productivity (edible biomass on a dry mass basis per area and time) based on reported planting density (blue) and on productivity derived from standard planting density parameter (pink). Data obtained from fully controlled environment experiments sourced from the literature.

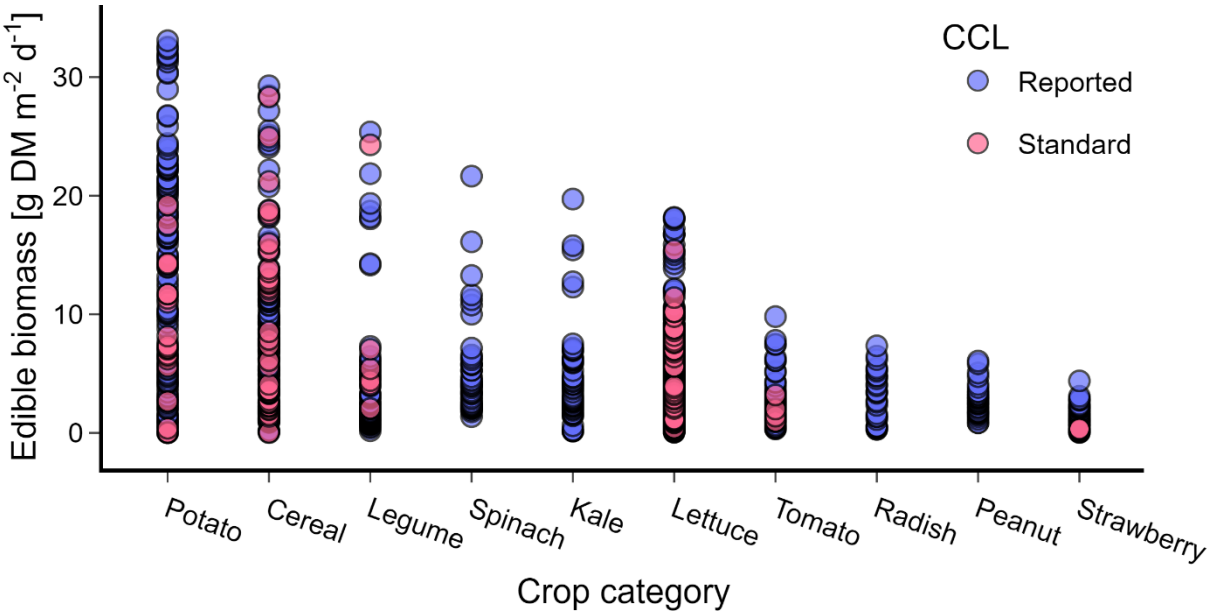

Figure S11 Correlation between calculated productivity (edible biomass on a dry mass basis per area and time) based on reported crop cycle length (CCL) (blue) and on productivity derived from standard CCL parameter (pink). Data obtained from fully controlled-environment experiments sourced from the literature.

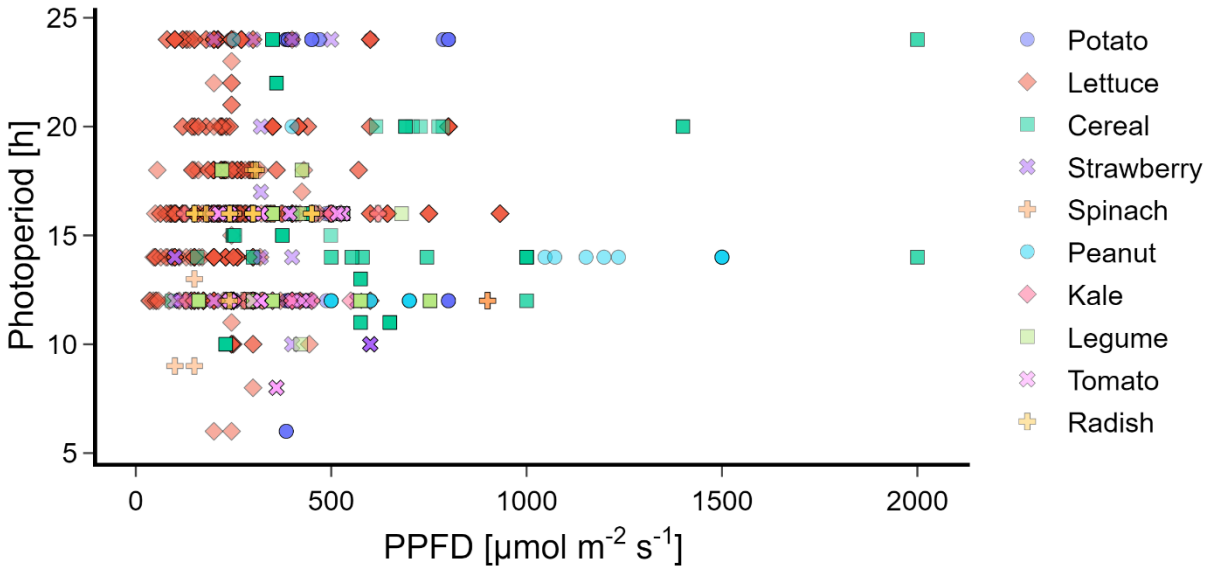

Figure S12 Distribution of photosynthetic photon flux density (PPFD) and photoperiod used as primary climate setting in the reported fully controlled-environment experiments. Various colors and symbols distinguish different crop categories.

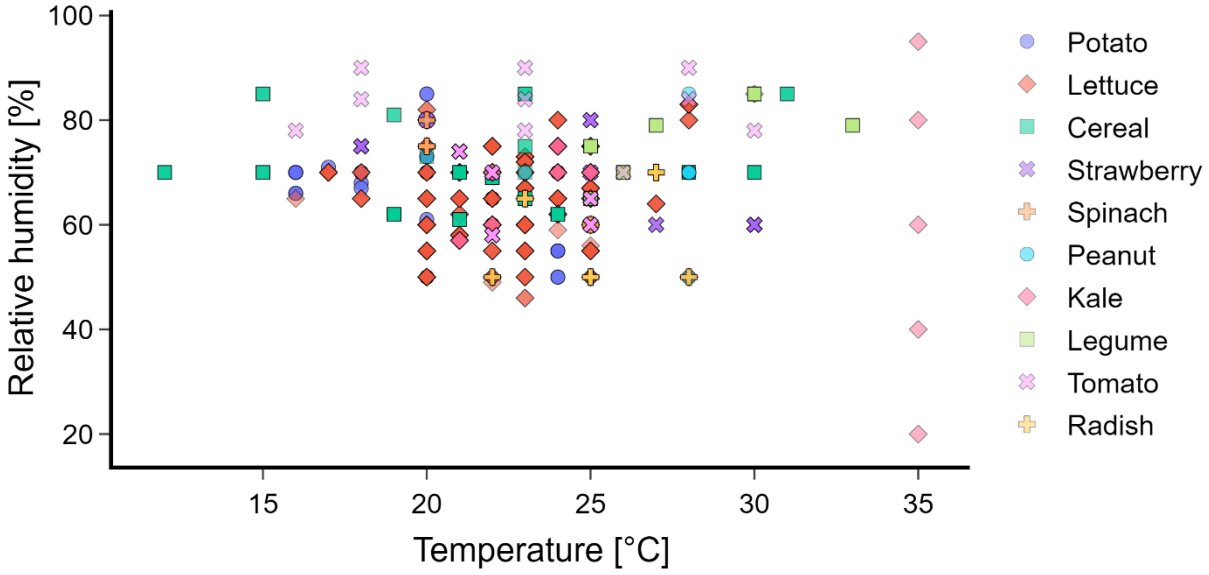

Figure S13 Distribution of temperature and relative humidity used as primary climate setting in the reported fully controlled-environment experiments. Various colors and symbols distinguish different crop categories.

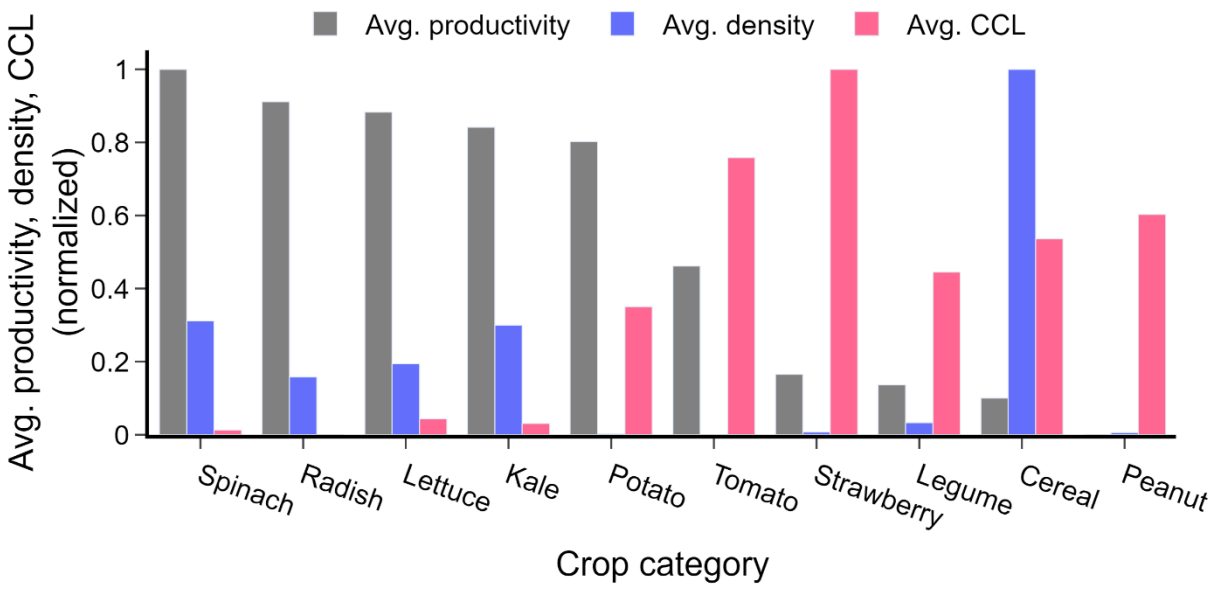

Figure S14 Comparison of average productivity (edible fresh mass per area and time) versus average plant density and average crop cycle length (CCL) for each crop category in fully controlled-environment experiments. Productivity, plant density, and CCL are all normalized on a scale of 0 to 1 across crop categories. Crop categories are arranged by productivity in descending order from left to right.

Table S1 Standard parameters for planting density and crop cycle length (CCL) from seeding to harvest for each crop type. The parameters represent the median of all reported data for planting density and crop cycle length of each crop type. Crop categories are primarily organized by taxonomical relationships, but the origin of the edible biomass is also considered, with some individual plant species directly delineated.

Crop type	Crop category	Std. plant density [plants m^{-2}]	Std. CCL [days]
Barley (*Hordeum vulgare L.)*	Cereal	240	128
Beet (*Beta vulgaris L.*)	Beet	18	56
Cabbage (*Brassica chinensis L.*)	Kale	3	40
Cowpea (*Vigna unguiculata (L.) Walp.*)	Legume	19	70
Endive (*Cichorium intybus L.*)	Lettuce	94	28
Green onion (*Allium fistulosum L.*)	Onion	750	35
Kale (*Brassica oleracea L.*)	Kale	100	42
Komatsuna (*Brassica campestris L.*)	Kale	74	32
Lentil (*Lens culinaris Medik.*)	Legume	100	110
Lettuce (*Lactuca sativa L.*)	Lettuce	35	35
Oat (*Avena sativa L.*)	Cereal	118	91
Pakchoi (*Brassica rapa L.*)	Kale	44	40
Pea (*Pisum sativum L.*)	Legume	102	84
Peanut (*Arachis hypogaea L.*)	Peanut	16	110
Pepper (*Capsicum annuum L.*)	Pepper	10	177
Potato (*Solanum tuberosum L.*)	Potato	11	90
Radish (*Raphanus sativus L.*)	Radish	27	35
Rice (*Oryza sativa L.*)	Cereal	300	95
Soybean (*Glycine max L.*)	Legume	25	99
Spinach (*Spinacia oleracea L.*)	Spinach	74	34
Strawberry (*Fragaria x ananassa L.*)	Strawberry	20	135
Sweet potato (*Ipomoea batatas (L.) Lam.*)	Sweet potato	48	129
Tomato (*Solanum lycopersicum L.*)	Tomato	11	128
Wheat (*Triticum aestivum L.*)	Cereal	226	103

Table S2 Standard moisture for each crop. The last two rows feature formulas for calculating dry mass from given fresh mass and vice versa, utilizing the standard moisture. Standard moisture parameters for crop types were sourced from the USDA National Nutrient Database (NDB) for Standard Reference from 2018, including NDB numbers and descriptions (U.S. Department of Agriculture [USDA], 2018). For komatsuna (*Brassica campestris L.*), a specific moisture value was unavailable; therefore, the value for the closely related species, Pakchoi, was utilized.

Crop type	Std. moisture [%]	NDB number (USDA)	NDB Description (USDA)
Barley (*Hordeum vulgare L.*)	10.1	20005	Barley, pearled, raw
Beet (*Beta vulgaris L.*)	88.2	11080	Beet, raw
Cabbage (*Brassica chinensis L.*)	91.9	11109	Cabbage, green, raw
Cowpea (*Vigna unguiculata (L.) Walp.*)	77.2	11191	Cowpea, immature seeds, raw
Endive (*Cichorium intybus L.*)	93.8	11213	Endive, raw
Green onion (*Allium fistulosum L.*)	89.1	11282	Onion, raw
Kale (*Brassica oleracea L.*)	89.6	11233	Kale, raw
Komatsuna (*Brassica campestris L.*)	95.3	11116	Cabbage, chinese (pak-choi), raw
Lentil (*Lens culinaris Medik.*)	9.45	100312	Lentil, dry
Lettuce (*Lactuca sativa L.*)	94	11253	Lettuce, leaf, green, raw
Oat (*Avena sativa L.*)	10.2	20038	Oat
Pakchoi (*Brassica rapa L.*)	95.3	11116	Cabbage, chinese (pak-choi), raw
Pea (*Pisum sativum L.*)	78.9	11304	Pea, green, raw
Peanut (*Arachis hypogaea L.*)	6.5	16087	Peanut, all types, raw
Pepper (*Capsicum annuum L.*)	93.9	11333	Pepper, sweet, green, raw
Potato (*Solanum tuberosum L.*)	79.2	11352	Potato, flesh and skin, raw
Radish (*Raphanus sativus L.*)	95.3	11429	Radish, raw
Rice (*Oryza sativa L.*)	12.4	20040	Rice, brown, medium-grain, raw
Soybean (*Glycine max L.*)	8.54	16108	Soybean, mature seeds, raw
Spinach (*Spinacia oleracea L.*)	92.4	11457	Spinach, mature
Strawberry (*Fragaria x ananassa L.*)	90.8	9316	Strawberry, raw
Sweet potato (*Ipomoea batatas (L.) Lam.*)	77.3	11507	Sweet potato, raw, unprepared

Tomato (*Solanum lycopersicum L.*)	92.5	100147	Tomatoes, grape, raw
Wheat (*Triticum aestivum L.*)	13.1	20072	Wheat, hard red winter

$$\boldsymbol{Dry\ mass = Fresh\ mass \times \frac{100 - Std.moisture}{100}}$$

$$\boldsymbol{Fresh\ mass = \frac{Dry\ mass \times 100}{100 - Std.moisture}}$$

Table S3 Conversion parameter from single pot sizes into squares of surface area (Plant Pot Size Guide, Johnsons Nurseries) and plant density assuming no space between the pots.

Pot volume [Liters]	Length [cm]	Width [cm]	Area [m^2]	Plant density [plants m^{-2}]
1	13	13	0.0169	59
2	17	17	0.0289	35
3	19	19	0.0361	28
4	20	20	0.04	25
5	22.5	22.5	0.050625	20
7	25	25	0.0625	16
10	28	28	0.0784	13
15	33	33	0.1089	9
20	35.5	35.5	0.126025	8
25	38.5	38.5	0.148225	7
30	41	41	0.1681	6
40	50	50	0.25	4

Table S4 Classification of crop types from fully controlled-environment experiments sourced from the literature into crop categories. Crop categories are primarily organized by taxonomical relationships, but the origin of the edible biomass is also considered, with some individual plant species directly delineated. Brackets following the crop type indicate the scientific name of the species.

Crop category	Family	Crop type
Cereal	Poaceae	Barley *(Hordeum vulgare L.)*
Cereal	Poaceae	Oat *(Avena sativa L.)*
Cereal	Poaceae	Rice *(Oryza sativa L.)*
Cereal	Poaceae	Wheat *(Triticum aestivum L.)*
Kale	Brassicaceae	Cabbage *(Brassica chinensis L.)*
Kale	Brassicaceae	Kale *(Brassica oleracea L.)*
Kale	Brassicaceae	Komatsuna *(Brassica campestris L.)*
Kale	Brassicaceae	Pakchoi *(Brassica rapa L.)*
Legume	Fabaceae	Cowpea *(Vigna unguiculata (L.) Walp.)*
Legume	Fabaceae	Pea *(Pisum sativum L.)*
Legume	Fabaceae	Soybean *(Glycine max L.)*
Legume	Fabaceae	Lentil *(Lens culinaris Medik.)*
Lettuce	Asteraceae	Endive *(Cichorium intybus L.)*
Lettuce	Asteraceae	Lettuce *(Lactuca sativa L.)*
Peanut	Fabaceae	Peanut (*Arachis hypogaea L.*)
Potato	Solanaceae	Potato (*Solanum tuberosum L.*)
Radish	Brassicaceae	Radish (*Raphanus sativus L.*)
Spinach	Chenopodiaceae	Spinach (*Spinacia oleracea L.*)
Strawberry	Rosaceae	Strawberry (*Fragaria x ananassa L.*)
Tomato	Solanaceae	Tomato (*Solanum lycopersicum L.*)
Beet	Chenopodiaceae	Beet *(Beta vulgaris L.)*
Onion	Alliaceae	Green onion *(Allium fistulosum L.)*
Pepper	Solanaceae	Pepper *(Capsicum annuum L.)*
Sweet potato	Convolvulaceae	Sweet potato *(Ipomoea batatas (L.) Lam.)*

References

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., . . . Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ (Clinical Research Ed.)*, *372*, n71. https://doi.org/10.1136/bmj.n71

U.S. Department of Agriculture. (2018). *FoodData Central: USDA National Nutrient Database for Standard Reference*. https://fdc.nal.usda.gov/