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Issues and Prospects for the Sustainable Use and Conservation of Cultivated Vegetable Diversity for More Nutrition-Sensitive Agriculture

Gennifer Meldrum [1,*], Stefano Padulosi [1], Gaia Lochetti [1], Rose Robitaille [1] and Stefano Diulgheroff [2]

1. Healthy Diets from Sustainable Production Systems Initiative, Bioversity International, Via dei Tre Denari, 472/a 00054 Maccarese, Italy; s.padulosi@cgiar.org (S.P.); g.lochetti@cgiar.org (G.L.); r.robitaille@cgiar.org (R.R.)
2. Plant Production and Protection Division, Food and Agriculture Organization of the United Nations, Viale delle Terme di Caracalla, 00153 Rome, Italy; Stefano.Diulgheroff@fao.org

* Correspondence: g.meldrum@cgiar.org; Tel.: +39-06-6118272

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Abstract: Traditional vegetables are key assets for supporting more nutrition-sensitive agriculture under climate change as many have lower water requirements, adaptation to poor quality soils, higher resistance to pests and diseases, and higher nutritional values as compared to global vegetables. The effective use of traditional vegetables can be challenged however by lack of information and poor conservation status. This study reviewed the uses, growth forms and geographic origins of cultivated vegetables worldwide and the levels of research, ex situ conservation, and documentation they have received in order to identify gaps and priorities for supporting more effective use of global vegetable diversity. A total of 1097 vegetables were identified in a review of the Mansfeld Encyclopedia of Agricultural and Horticultural Plants, including species used for leaves (n = 495), multiple vegetative parts (n = 227), roots (n = 204), fruits or seeds (n = 90), and other parts like flowers, inflorescences, and stems (n = 81). Root vegetables have received significantly less research attention than other types of vegetable. Therophytes (annuals) have received significantly more attention from research and conservation efforts than vegetables with other growth forms, while vegetables originating in Africa (n = 406) and the Asian-Pacific region (n = 165) are notably neglected. Documentation for most vegetable species is poor and the conservation of many vegetables is largely realized on farm through continued use. Supportive policies are needed to advance research, conservation, and documentation of neglected vegetable species to protect and further their role in nutrition-sensitive agriculture.

Keywords: traditional crops; cultivated vegetables; neglected and underutilized species; nutrition; climate change adaptation

1. Introduction

Vegetables are important sources of micronutrients, including vitamins, minerals, antioxidants and fibre needed to conduct a healthy and productive life [1,2]. They are among the most diverse, colourful and tastiest foods, and are strategic for reaching balanced diets and reducing the incidence of severe health ailments [1,3]. Current nutrition guidelines recommend consumption of at least 400 g (5 portions) of fruits and vegetables per day [4], yet a large proportion of individuals do not meet these requirements, which is contributing to rates of malnutrition and the rise of non-communicable diseases around the world [5–7].

Links between agriculture and nutrition are well documented and historic trends in agricultural development are acknowledged to have contributed to current diet insufficiencies [8,9].

The calorie-centric approach focused on enhancing yields of a few staple cereals through the Green Revolution has led to a profound loss of diversity in agriculture and food systems. Rice, wheat and maize account for 51 percent of plant-based caloric intake and 42 percent of the total food supply (kcal/capita/day) in human diets, meanwhile their cultivation covers 40% of arable land globally [10]. In comparison to the major cereals, investments in research and development for vegetables have been negligible and focused mainly on a small basket of globally-important crops [11]. Production of vegetables and fruits is currently insufficient to meet the needs of the human population, with supply deficits of 22% on average and up to 58% in low-income countries [12]. Value chains for vegetables are, moreover, poorly developed in many places, which limits their accessibility to consumers [13–16]. Enabling access to vegetables at an affordable price is both an emerging priority and a challenge for policy makers as populations become increasingly urbanized and reliant on purchased foods [17–20].

In recognizing the need for nutrition-sensitive agriculture and food systems, greater vegetable production and use are being called for and promoted through horticulture, home gardens, urban and peri-urban agriculture, agroforestry, and school feeding programmes, among other approaches [21–28]. As well as supplying nutritious food, vegetable production is also recognized as a profitable sector that can support income generation [11,29]. While having great potentials, vegetable cultivation also faces important agronomic challenges and limitations, especially with regards to water availability, soil fertility, and pest and disease control. It is highly sensitive to climate change [30–33] and can enhance vulnerability of producers in water limited areas [34,35], as well as exposure to harmful chemical inputs [34,36–38]. To ensure a holistically sustainable development trajectory, the transformation towards vegetable-rich production and food systems should also support climate change adaptation and protection of human and environmental health [39].

Traditional vegetables are an important asset for meeting this challenge as many have high nutritional value, low water requirements, adaptation to poor quality soils, and good resistance to pests and diseases [40–45]. Several indigenous leafy vegetables of Africa present an optimal source of nutrients such as β-carotene, folate, iron, calcium, zinc, proteins and dietary fibre [46–49], while showing lower water use and higher water use efficiency compared to introduced vegetables such Swiss chard (*Beta vulgaris* subsp. *Vulgaris* L.) [50]. Chaya (*Cnidosculus aconitifolius* (Mill.) I.M. Johnst) is a shrub native to Mesoamerica that thrives with few inputs in arid conditions and produces leaves with two to three times the nutrient value of spinach and lettuce [51,52]. The greater content of important macro and micronutrients found in many traditional vegetables is partly the result of crop improvement favouring selection of traits such as high yield, shelf life, and appearance, while neglecting traits such as vitamin and mineral content [44,53,54]. Traditional vegetables can also require relatively fewer labour and economic inputs compared to global vegetables, meaning they present lower risks of financial losses for small farmers [55]. Because of their nutritional values and local adaptation, there is a growing body of literature highlighting how greater production and consumption of traditional and indigenous vegetables can support nutrition security and incomes [46,56–59]. However, more research is needed to clarify and leverage the roles and potentials of specific species, as the complex relationships between nutritional yields, water availability, and soil quality [60,61] remain underexplored for many species, as do their acceptability to consumers and capacities for integration in value chains.

Lack of knowledge and research generally challenges the promotion and use of traditional vegetables. Similar to other neglected and underutilized crop species, traditional vegetables are characterized by limited research efforts, breeding efforts, germplasm characterization, knowledge on species distribution and production levels, and representation in ex situ collections [62]. A dearth of information and poor awareness may allow useful species to be overlooked through a vicious cycle of neglect and underutilization. Declining use and eroding knowledge of traditional vegetables has been observed in many places around the world, which threatens their persistence into the future and limits the delivery of their benefits to society [63,64]. One million accessions are kept in world gene banks for vegetable crops but they mainly cover a small number of commodity crops (viz. tomatoes, capsicums, melons and cantaloupe, brassicas, cucurbits, alliums, okra, and eggplant) and crops with important non-vegetable uses such as grain, pulse or fibre [65]. The state of conservation of traditional vegetables remains largely underexplored and poorly documented but many are likely conserved primarily through continued cultivation on-farm, which is a fragile situation where their use is declining [45].

This study aimed to shed light on the diversity of cultivated vegetables worldwide and to highlight opportunities to leverage neglected and underutilized species for more nutrition-sensitive agriculture. A database of cultivated vegetable species was compiled by review of the Mansfeld Encyclopedia of Agricultural and Horticultural Crops [66] and trends and gaps for their research, conservation, and documentation were evaluated in relation to their uses, growth forms, and geographic origins. The results reveal priority areas for research and development which can help to build the knowledge base and strengthen the conservation of vegetable diversity to support its integration in more nutrition-sensitive production systems.

2. Materials and Methods

A database of cultivated vegetable species was compiled for the study based on the 3rd edition of the Mansfeld's Encyclopedia of Agricultural and Horticultural Crops [66]. This resource covers more than 6040 species cultivated by humans, excluding ornamentals. The list of species has been *compiled through comprehensive reviews of the scientific literature and contributions from botanical institutes, gardens, and research centers around the world* [66,67]. It is among the most thorough databases of cultivated plants at the global level and has been used in previous assessments of cultivated plant diversity [68,69]. Existing global reviews of vegetable species (e.g., [70,71]) do not explicitly include all minor and traditional vegetables cultivated in local food systems. The Mansfeld Encyclopedia was selected because it best matched the objective and scope of the study to consider all cultivated vegetables, including minor species, while following a consistent format suitable for global level analysis.

Any plant part consumed for food that is not a mature fruit or seed is by definition a vegetable, meanwhile fruits (and legume pods) prepared in salads and savoury dishes are also considered vegetables in a culinary sense [72]. All plant species with vegetative parts consumed or for which fruits and seeds were explicitly mentioned to be consumed as a vegetable in the Mansfeld Encyclopedia were included in the database (Database S1). Non-vegetable uses of the seed (as cereals, grains or pulses) and fruit (consumed as a sweet or tart snack, dessert or side dish) were noted. The distinction between vegetable and non-vegetable uses for the fruits and seeds was challenging and arbitrary in some cases because it is based on perception and preparation. For this reason, we acknowledge that some inconsistencies have likely occurred in the database. To enable comparisons with other databases, the list of cultivated vegetables was standardized to accepted synonyms on the Plant List (http://www.theplantlist.org), which is a noble attempt toward a comprehensive online database of all plant species initiated by Royal Botanic Gardens, Kew, and the Missouri Botanical Garden [73]. The process of standardizing the synonyms was automated using the Taxonstand package in R [74]. Unresolved species were maintained that did not have other potential synonyms in the list.

2.1. Species Characterization

For all the species in the database, the specific part/s used as a vegetable were scored. In cases when the parts utilized as vegetable were unclear or unspecified in the Mansfeld Encyclopedia, additional credible data sources were consulted for clarification. Five distinct groups of vegetables were defined based on their use: "leafy vegetables" that are used for their leaves and which may also be used for their shoots; "root vegetables" for which roots, tubers, rhizomes, corms or bulbs are used; "fruit and seed vegetables" for which the fruit, pods, or fresh seeds are used as vegetables; "other vegetables" used for other specific parts such as flowers, stems, and shoots, and "multiuse vegetables" which, in contrast to the previous groups, have multiple parts used as vegetables. This grouping was made with reference to exploratory analyses with multiple correspondence analysis (MCA) and hierarchical clustering in the FactoMineR package in R.

In addition to plant uses, the geographic region of origin for each vegetable species was also documented. Each species was classified based on the notes in the Mansfeld Encyclopedia regarding countries and ranges of cultivation into the twelve cradles of agriculture and centres of diversity proposed by Zeven and Zhukovsky [75]. Following a similar process as for classifying species into use typologies, species were assigned into five groups reflecting common geographic origin. Species were grouped together that had a clear origin in (1) the Americas; (2) Saharan and sub-Saharan Africa; (3) the region spanning Europe, the Mediterranean, the Near East, and Central Asia; and (4) Asia, Australia and the Pacific Islands. A fifth group included wider ranging species whose origin was unclear or which spanned several regions.

Literature searches were furthermore performed for each vegetable species to classify them by growth form. The Raunkiaer life form system [76] as modified by Govaerts and colleagues [77] was applied, which is a fairly simple and widely used classification for plants that relates to many aspects of plant ecology, including reproductive mode, lifespan, and associated climate [78,79]. The Raunkiaer life forms are defined based on how species survive in unfavourable seasons and particularly how well the vegetative buds are protected. Further detail on the classification is provided in Table 1. In addition to classifying the cultivated vegetables by these 10 life-forms, additional characterization as climbing, succulent and parasitic plants was followed as per Govaerts et al. [77].

Table 1. Growth form classification of plant life forms sensu Raunkiaer [76] and Govaerts et al. [77].

Life Form	Characteristics
Phanerophytes	Persistent woody stems and buds that project 3 m or more above the soil. Includes trees and large shrubs, e.g., *Moringa oleifera* Lam.
Nanophanerophytes	Woody, persistent stems, with buds located between 0.5 m and 3 m above ground level. Includes smaller shrubs, e.g., *Cordyline fruticosa* (L.) A. Chev.
Herbaceous phanerophytes	Herbaceous stems projecting more than 0.5 m above ground level that persist for several years. Includes many tropical species, e.g., *Musa acuminata* Colla.
Chamaephytes	Persistent stems that are herbaceous or woody with buds located above soil level, but never by more than 0.5 m. Includes dwarf shrubs and some perennial herbs, e.g., *Aloe macrocarpa* Tod.
Hemicryptophytes	Herbaceous stems that often die-back during unfavourable seasons with surviving buds placed on (or just below) soil level. Includes many biennial and perennial herbs, including those in which buds grow from a basal rosette, e.g., *Lactuca sativa* L.
Geophytes	Stems that die back during unfavourable seasons with the plant surviving as a bulb, rhizome, tuber or root bud, e.g., *Daucus carota* L.
Therophytes	Complete their entire life-cycle during the favourable season and survive the unfavourable season as a seed. This group includes all annual herbs, e.g., *Corchorus olitorius* L.
Epiphytes	Growing buds occur on another plant, e.g., *Peperomia pereskiifolia* (Jacq.) Kunth.
Helophytes	Surviving buds are buried in water-saturated soil, or below water-level, but with flowers and leaves that are fully emergent during the growing season. Includes many marsh plants and emergent aquatic herbs, e.g., *Typha latifolia* L.
Hydrophytes	Fully aquatic herbs in which surviving buds are submerged, or buried in soil beneath water. Stems and vegetative shoots grow entirely underwater and leaves can be submerged or floating, but only the flower-bearing parts may be emergent, e.g., *Vallisneria natans* (Lour.) H.Hara.

2.2. Indicators of Neglect

Three indicators of neglect from research and development were assessed for each of the cultivated vegetable species following a similar approach to Galluzzi and Lopez Noriega [62], as described below.

Firstly, the number of records in Google scholar was used as an indication of research effort devoted to the species. Google scholar is a well utilized and robust index of academic literature from multiple disciplines that concern agriculture, including the social sciences and life sciences [80]. Google Scholar has some disadvantages compared to more controlled databases, including full-text rather than field-level search, lack of controlled vocabulary [81] and duplicated-records [82]. However, the coverage and accuracy has greatly improved over time and the index has some important advantages. In particular, accessibility was an important criterion for this review and a primary reason why Google Scholar was preferred over subscription based databases [83]. Comparisons of Google Scholar search results to other databases show a strong overlap [80]. A search was conducted for each species including the genus and species epithet as required words to be included along with at least one of the words "nutrition", "food" or "vegetable". This specification was made to help limit the search results to food uses and exclude studies relating mainly to pharmacology and other aspects. The search was limited to the previous 20 years (1997–2017) and was performed for the established synonym(s).

Secondly, the number of accessions maintained in ex situ germplasm collections worldwide was assessed using the World Information and Early Warning System on Plant Genetic Resources for Food and Agriculture database (WIEWS). The WIEWS database provides access to official figures on the number of plant genetic resources for food and agriculture secured in either medium- or long-term conservation facilities, as part of the monitoring of the implementation of the Second Global Plan of Action for Plant Genetic Resources for Food and Agriculture, and the plant component of Sustainable Development Goal indicator 2.5.1. The total number of accessions maintained for each cultivated vegetable species was queried by searching the established synonym and additional common synonyms.

Thirdly, production data from the Food and Agriculture Organization of the United Nations Statistical Databases (FAOSTAT) were used as an indicator of knowledge on species distribution and production levels. These agricultural statistics are reported by member nations and collected from agricultural yearbooks and other publications [84]. The data are not always based on direct observations, which results in some inconsistencies. Nonetheless, they a rare standardized source of cropping information and a pillar for global analyses of crop production [84,85]. Data for vegetables in FAOSTAT primarily concern those grown for human consumption in field and market gardens, while excluding those grown in small family gardens for household consumption. It is noted that significant gaps in the coverage of FAOSTAT would naturally exclude some of the vegetable species covered in this review. However, as this database represents a standard for agricultural production statistics and reflects on the detail of data collected by nation states, it was considered as a reasonable indicator of documentation (and knowledge) of species distribution and production levels. The number of countries with official data for different vegetables over the past 20 years (1997–2016) was assessed.

2.3. Relating Indicators of Neglect to Use, Growth Form and Region of Origin

The relationship between the three indicators of neglect (number of Google scholar records, number of accessions, and documentation in FAOSTAT) and species characteristics (region of origin, growth form, and vegetable and non-vegetable uses) were explored using statistical analyses. Welch's Analysis of Variance (ANOVA) was applied to test how the number of Google scholar records and accessions maintained in world gene banks relate to species characteristics. Welch's ANOVA is suitable for cases with unequal variance and sample sizes between groups but it assumes the sample conforms to a normal distribution, which was achieved by log-transformation. Following a similar approach to other researchers [86,87], post hoc pairwise comparisons were made using Games and Howell tests, which have similar assumptions and are consistent with Welch's ANOVA [88,89]. Chi-square tests were similarly used to assess how the probability of being included in FAOSTAT (either as a specific species or as part of a group of vegetables) related to species characteristics. In this case, Fisher exact tests were applied for post hoc pairwise comparisons. All analyses were performed using R version

3.4.3 (R Foundation for Statistical Computing, Vienna, Austria) in R Studio version 1.1.383 (RStudio, Inc., Boston, MA, USA).

3. Results

A total of 1097 cultivated vegetable species from 133 families and 544 genera were identified in the study. The families with greatest number of cultivated vegetable species were the Leguminosae (*n* = 127), Compositae (*n* = 85), Dioscoreaceae (*n* = 56), Amaranthaceae (*n* = 45) and Araceae (*n* = 44). The genera with the most cultivated vegetable species were the Dioscorea (*n* = 54), Solanum (*n* = 26) and Allium (*n* = 26). Almost all species had accepted synonyms but 32 species names were unresolved.

3.1. Uses

Various plant parts are used as vegetables including above-ground vegetative structures like leaves (58%), shoots (15%), and stems (3%), underground vegetative structures such as tubers (12%), rhizomes (5%), roots (4%), bulbs (3%), and corms (2%), and reproductive structures like flowers and inflorescences (13%), ripe or unripe fruits (10%), and fresh seeds (4%). The majority (75%) of the cultivated vegetables have only one plant part used as a vegetable, while a quarter (25%) have multiple parts used as vegetables. Numerous vegetable species also have non-vegetable food uses such as fruit (12%) and grain/pulse (9%). *Parkia speciosa* Hassk. was the species with the most parts utilized as vegetables including the leaves, thickened inflorescences, sprouts, fruits, and seeds. Other species with many parts used as vegetables are *Moringa oleifera* Lam., *Momordica dioica Roxb.* ex Willd., *Benincasa hispida* (Thunb.) Cogn., *Sechium edule* (Jacq.) Sw., *Dioscorea praehensilis* Benth., *Nelumbo nucifera* Gaertn., *Aponogeton distachyos* L.f., *Psophocarpus grandifloras* R.Wilczek, and *Psophocarpus scandens* (Endl.) Verdc. Five groups of vegetables were defined based on their use typology: 45% are used primarily for their leaves; 19% are primarily used for underground vegetative parts (roots, tubers, corms, rhizomes, or bulbs); 8% have fruits and/or seeds used as vegetables; 7% have other vegetative parts used as vegetables such as flowers, inflorescences, stems, and shoots and 21% have multiple parts used as vegetables (Table 2).

Table 2. Use typology of cultivated vegetable species.

	Leafy Vegetables (*n* = 495)	**Root Vegetables (*n* = 204)**	**Fruit/Seed Vegetables (*n* = 90)**	**Other Vegetables (Flower, Stem, Shoot) (*n* = 81)**	**Multiuse Vegetables (*n* = 227)**
Parts used as a vegetable					
Leaves	100%				63%
Shoots, sprouts	14%			46%	25%
Stems				15%	12%
Bulb		13%			5%
Corm		9%			2%
Tuber		52%			12%
Rhizome		15%			10%
Roots		12%			11%
Flowers, petals, inflorescences				40%	48%
Fruit/pod			77%		18%
Fresh seed			30%		7%
Parts used for non-vegetable uses					
Seed	8%	1%	27%		16%
Fruit	12%	2%	20%		25%

3.2. Growth Forms

The most common growth forms of the cultivated vegetables are geophytes (33%) and therophytes (22%) (Figure 1). Phanerophytes (18%), nanophanerophytes (10%) and herbaceous phanerophytes (2%) together make up a sizable portion of the cultivated vegetables. Hemicryptophyte (6%), chamaephyte

(4%) and helophyte (4%) growth forms are less common, while only two hydrophyte (*Vallisneria natans* (Lour.) H.Hara and *Limnophila aromatic* (Lam.) Merr.) and four epiphyte (*Ficus rumphii* Blume; *Ficus annulata* Blume; *Begonia eminii* Warb.; and *Peperomia pereskiifolia* (Jacq.) Kunth) species were identified in the analysis. Of all the cultivated vegetables, 17% are climbing plants, which are mostly geophytes and therophytes. Just 3% are succulents, found mostly among the nanophanerophytes, chamaephytes, and therophytes.

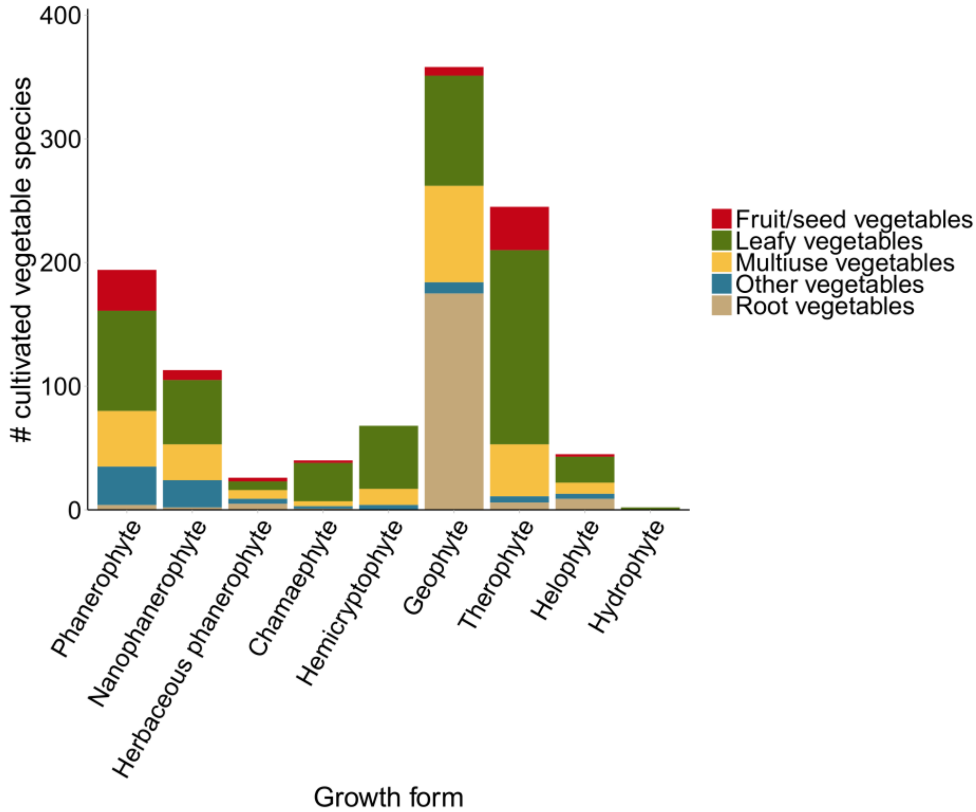

Figure 1. Growth forms of cultivated vegetable species with different uses worldwide.

3.3. Centre of Origin

The majority (72%) of cultivated vegetables have their centre of origin in just one of the world regions of crop diversity defined by Zeven and Zhukovsky [75]. Eighteen percent of the species have a wider centre of origin spanning two regions, while 10% have extensive ranges that span further than three regions. The widest ranging species include several pan-tropical (5%), Eurasian (2%), paleo-tropical (1%), and other species for which the centre of origin is unclear such as *Euphorbia hirta* L., *Neptunia oleracea* Lour., and *Laportea aestuans* (L.) Chew. Overall, 37% of cultivated vegetable species were determined to have an Asian–Pacific origin, 22% originated in the Americas, 17% are from the region spanning Europe, the Mediterranean, Near East and Central Asia, 15% originated from Saharan and sub-Saharan Africa, and 10% are wide ranging species that cross several world regions (Table S1). The geographic distribution of vegetables with different uses is shown in Figure 2.

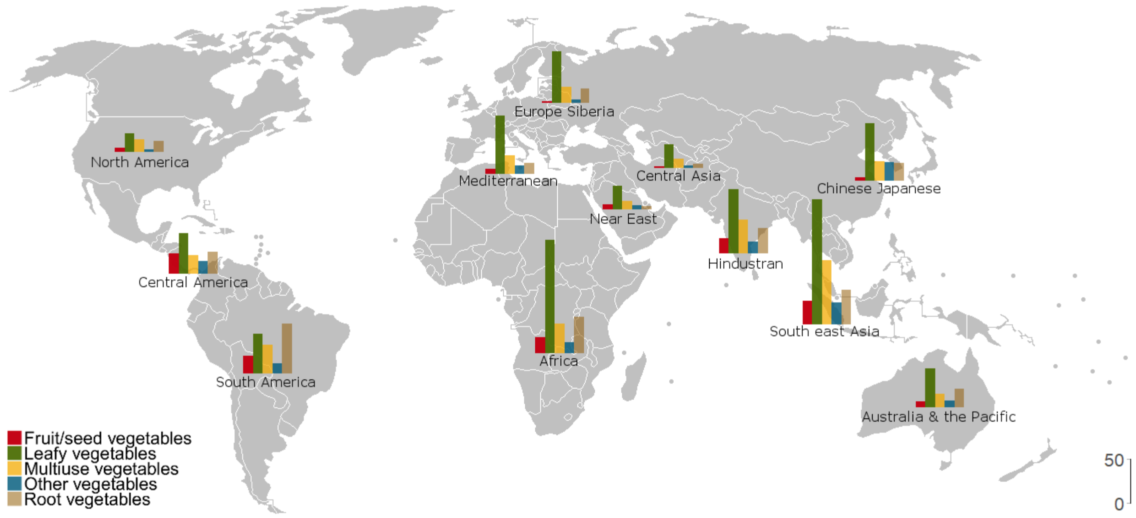

Figure 2. Number of cultivated vegetable species with different use types from different regions of diversity worldwide [75]. Base map courtesy of WikiMedia Commons.

3.4. Research

The number of Google scholar records relating to food, nutrition or vegetable uses for the cultivated vegetables ranged from 0 to 62,700 with a median of 382 (1st quartile 74; 3rd quartile 1700). No study relating to food, nutrition or vegetable uses was found for 13 of the species using the search query applied, while an additional 65 species had just 10 or fewer studies (Table S2). Many of these poorly studied vegetables were in the Dioscoreaceae ($n = 20$), Leguminosae ($n = 10$), Araceae ($n = 7$) and Compositae ($n = 5$) along with 25 other families. The best studied vegetable species were *Phaseolus vulgaris* L., *Glycine max* (L.) Merr., *Solanum lycopersicum* L., *Brassica napus* L., *Solanum tuberosum* L., *Pisum sativum* L., *Brassica oleracea* L., *Capsicum annuum* L., *Allium cepa* L., and *Vicia faba* L., each of which had more than 25,000 records in Google scholar.

The number of Google scholar records for vegetable species was significantly related to growth form, region of origin, and vegetable and non-vegetable uses (Welch's ANOVA, Table 3). Root vegetables had significantly fewer Google scholar records than all other types of vegetable (Figure 3A; Games-Howell test $p < 0.01$). The multi-use vegetables had significantly more Google scholar records than the leafy vegetables and other vegetables, as well as the root vegetables (Figure 3A; Games-Howell test $p < 0.05$). Species exclusively used as vegetables had significantly fewer Google scholar records than those with non-vegetable uses for the fruit or seed (mean 1822 ± 153 vs. 3916 ± 510; Table 3). The therophyte vegetables were by far the best researched with significantly more Google scholar records compared to chamaephyte, herbaceous phanerophyte, nanophanerophyte, phanerophyte, and geophyte vegetables (Figure 3B; Games–Howell test $p < 0.05$). Wide-ranging species and vegetables from the Europe-Mediterranean-Near East-Central Asia region had significantly more Google scholar records compared to species from Africa, the Asia-Pacific region, and the Americas (Figure 3C; Games–Howell test $p < 0.05$). Vegetables originating in Africa notably had received the lowest level of research attention, with significantly fewer Google scholar records compared to vegetables from all other regions of origin (Figure 3C; Games-Howell test $p < 0.05$).

Table 3. Results of statistical tests evaluating how indicators of neglect for cultivated vegetable species relate to growth form, region of origin, and vegetable and non-vegetable uses.

Factor	# Google Scholar Records [a]	# Accessions [a]	Documented in FAOSTAT [b]
Growth form	$F_{(7, 192.58)} = 9.84$ ***	$F_{(7, 195.5)} = 25.46$ ***	$X^2_{(7)} = 121.93$ ***
Region of origin	$F_{(4, 417.14)} = 20.94$ ***	$F_{(4, 399)} = 17.40$ ***	$X^2_{(4)} = 12.88$ *
Vegetable use	$F_{(4, 293.4)} = 18.78$ ***	$F_{(4, 299.1)} = 38.70$ ***	$X^2_{(4)} = 105.33$ ***
Non vegetable use	$F_{(1, 50.19)} = 50.19$ ***	$F_{(1, 299.1)} = 23.53$ ***	$X^2_{(1)} = 7.26$ **

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. [a], Welch's ANOVAs on log transformed data; [b], Chi-square tests on binary data (included as a specific species or in a group of species = 1; not included at all = 0).

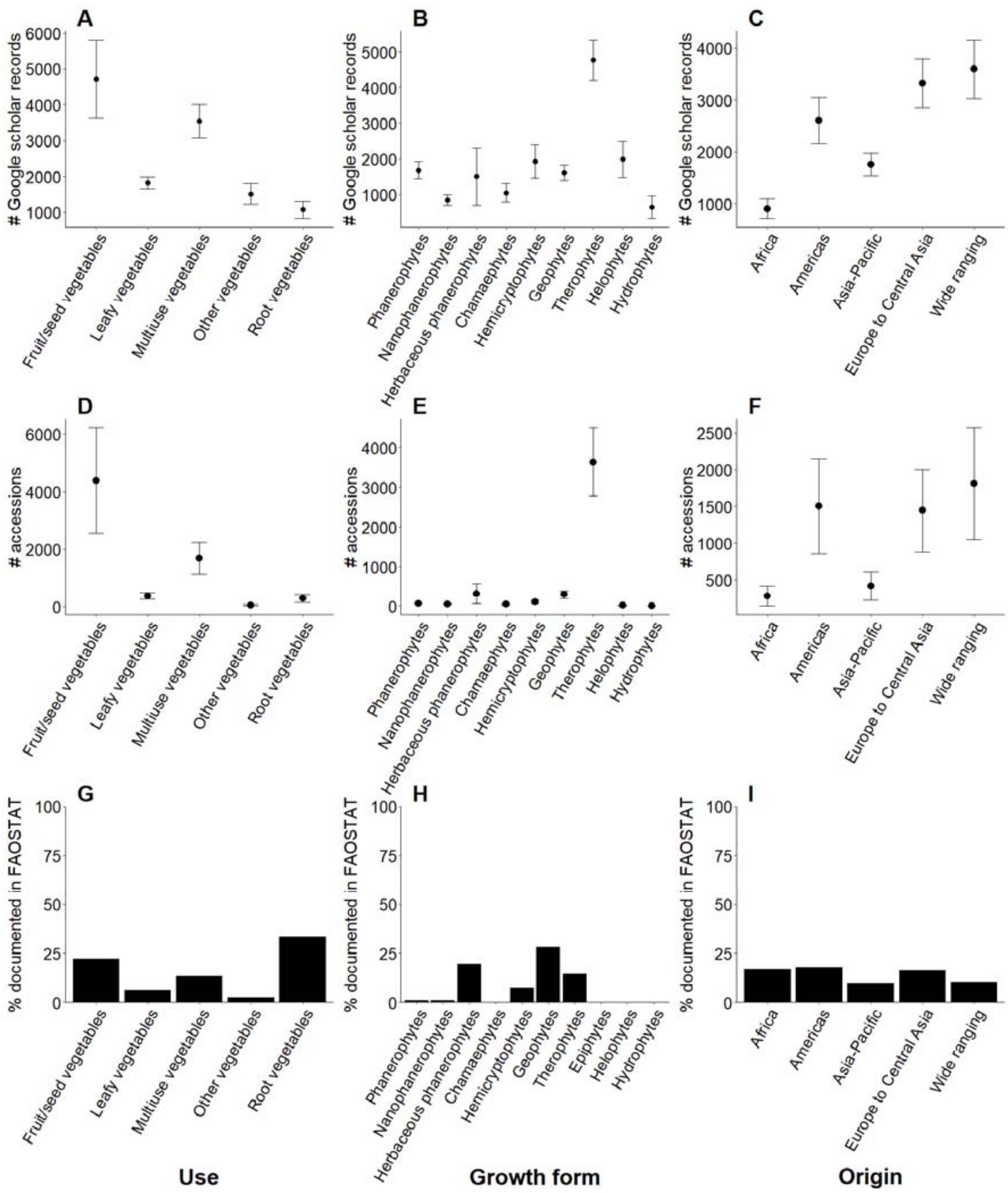

Figure 3. Mean (±standard error) number of Google scholar records relating to food, nutrition and vegetable uses for cultivated vegetables with different uses (**A**), growth forms (**B**), and regions of origin (**C**); mean (± standard error) number of accessions maintained in world genebanks for cultivated vegetables with different uses (**D**), growth forms (**E**), and regions of origin (**F**); and the percent of cultivated vegetable species with different uses (**G**), growth forms (**H**), and regions of origin (**I**) that were documented in FAOSTAT production statistics for at least one country in the previous 20 years.

3.5. Ex Situ Conservation

The number of accessions maintained for the cultivated vegetable species ranged from 0 to 142,040 with a median of 1251 accessions (1st quartile 1; 3rd quartile 50). No accessions were found to be maintained in the worlds' genebanks for 270 cultivated vegetable species (listed in Table S3). Many of the vegetables excluded from ex situ collections were in the families Dioscoreaceae (n = 34) and Araceae (n = 30) along with 79 other families. The 10 best conserved vegetable species with the most accessions were *Phaseolus vulgaris* L., *Glycine max* (L.) Merr., *Pisum sativum* L., *Solanum lycopersicum* L., *Vicia faba* L., *Capsicum annuum* L., *Solanum tuberosum* L., *Brassica oleracea* L., *Brassica napus* L. and *Allium cepa* L., which had more than 26,722 accessions each.

The number of accessions maintained by genebanks was significantly related to species' growth form, region of origin, and vegetable and non-vegetable uses (Welch's ANOVA; Table 3). Fruit/seed and multiuse vegetables had significantly more accessions than leafy vegetables, root vegetables and other vegetables (Figure 3D; Games–Howell test $p < 0.05$). Species exclusively used as vegetables had fewer genebank accessions compared to those that also had non-vegetable food uses for the fruit or seed (mean 411 $\pm$ 83 vs. 2980 $\pm$ 907; Table 3). The therophytes had significantly more accessions compared to chamaephytes, geophytes, helophytes, hemicryptophytes, phanerophytes, herbaceous phanerophytes, and nanophanerophytes (Figure 3E; Games-Howell test $p < 0.05$). The hemicryptophytes were also noted to have significantly higher numbers of accessions compared to the phanerophytes, nanophanerophytes and helophytes (Figure 3E; Games-Howell test $p < 0.05$). Vegetables from Africa and the Asia-Pacific region had significantly fewer accessions compared to species originating from the Americas and the Europe-Mediterranean-Near East-Central Asia region, as well as far-ranging species with origins spanning multiple regions (Figure 3F; Games-Howell test $p < 0.05$).

3.6. Production Data

There was a general paucity of production data in FAOSTAT for the cultivated vegetables. Only 19 species were documented specifically, while another 74 were documented in groupings that included several species, sometimes from distant taxonomic groups and including up to 20 congeners in the case of yams (Table S4). Some species could fit into multiple categories. For example, *Allium sativum* L. could be classified as "garlic" or among the "leeks and other allia". Overall, 92% of cultivated vegetable species were not covered by the database, or would only be potentially covered in very broad unspecific categories like "vegetables, fresh, not elsewhere specified" or "vegetables, leguminous, not elsewhere specified", which were excluded from our analysis for their generality. The likelihood of a species being included in FAOSTAT was significantly related to growth form, use, and region of origin (Chi-square test; Table 3). In contrast to the pattern seen for Google scholar records and genebank accessions, the root vegetables were found to have higher coverage in FAOSTAT compared to all other types of vegetable aside from fruit/seed types (Fisher exact test $p < 0.05$). The higher probability of geophytes being included in the database echoed this result (Fisher exact test $p < 0.05$). Leafy and 'other' vegetables, as well as phanerophyte and nanophanerophyte vegetables had the poorest coverage in FAOSTAT. Vegetables from the Asia-Pacific region had significantly lower probability of being included in FAOSTAT compared to those from the Americas (Fisher exact test $p < 0.05$).

4. Discussion

The results from this study confirm the existence of a large diversity of cultivated vegetables in most regions of the world, which is a rich basket of opportunities that can be harnessed to fight poverty, nutrition insecurity and vulnerability to climate change. Of the 1097 cultivated vegetables, few were found to have received substantial coverage by research, ex situ conservation, and production statistics (Table S5). Most vegetables have instead received scant attention from research and conservation efforts and their production remains poorly documented. The potential of traditional vegetables is increasingly recognized for supporting more nutritious and sustainable production and food systems [40–45], however a lack of knowledge and conservation of these species can challenge efforts for their promotion [90,91]. Clear patterns were observed regarding levels of research, conservation, and documentation of vegetables with different growth forms, uses, and regions of origin, which highlighted some priority areas to help advance the role of vegetable diversity for nutrition sensitive agriculture, as discussed in the following paragraphs.

Five use typologies of vegetables were distinguished in the study, which have received different levels of research attention. Root vegetables stood out for having significantly fewer Google scholar records compared to all other types of vegetables, calling attention to this group as potentially deserving greater research attention. The major nutritional contribution of many root vegetables is starch [1,4], but their food and nutrition security contributions can be important as they can provide important sources of health-promoting vitamins and minerals [92–94]. For example, Andean roots and tubers, such as oca (*Oxalis tuberosa* Molina) and mashua (*Tropaeolum tuberosum* Ruiz and Pav.) present distinct amino acid compositions and are rich in ascorbic acid that is fundamental for optimal absorption of iron [95]. In addition to the roots, neglected leafy vegetables and species used for stems, shoots, and flowers may also merit greater research attention as these plant parts can provide important macro and micro nutrients to diets [46–49,96,97] and they were found to have received lower research attention than the multiuse vegetables. Since more than half of cultivated vegetables (58%) are used primarily for their leaves, we note that this large and poorly studied group of species could indeed offer a great diversity of opportunities for supporting more nutrition-sensitive agriculture.

Cultivated vegetables come in a variety of growth forms including trees, shrubs, herbs, and water plants. The therophyte (annual) vegetables are by far the best researched and conserved, while other growth forms are comparatively neglected. The poor ex situ conservation of non-annual plants may relate to challenges posed by their biology and their perceived economic values. Annuals are well suited to ex situ conservation, which primarily involves storage of seeds in cold chambers [98]. Other major growth forms of vegetable such as geophytes, phanerophytes, and nanophanerophytes are often clonally propagated or have recalcitrant seeds that are sensitive to desiccation and/or cold [99,100]. The majority of plant species with recalcitrant seeds are shrubs or trees, of which about half are found in tropical moist forests [101]. Adequate representation of the genetic diversity of such species in ex situ collections poses difficulties as they must be conserved either in field genebanks or in vitro, while the processes and research required to establish their conservation may prove cost ineffective [98,102,103]. In view of these constraints, conservation of the genetic diversity of many cultivated vegetables is likely to depend in large part on in situ/on farm conservation [104]. As the use of traditional crops and transmission of associated knowledge are observed to be decreasing in many parts of the world [63,105], attention to reverse these trends are paramount to ensure the maintenance of these resources into the future.

Neglected vegetables are found in all world regions but a strikingly low amount of research and few genebank accessions are dedicated to species from Africa and the Asia-Pacific region. This pattern results from the narrow focus of research and development on major staples, as well as other historical and cultural factors that have shaped priorities in production and market development in these regions [8,106–109]. Traditional vegetables are recognized as strategic assets to reduce high rates of malnutrition that persist in Africa and Asia due to the strong nutritional values, seasonal availability, and capacity to thrive on poor soils under water limited conditions that characterize many species [46,56,110]. Important steps are already being taken for promotion of traditional vegetables towards this end [111–113]. Notably, the World Vegetable Centre (AVRDC) is conducting selection programmes for indigenous Asian and African vegetables in addition to their active breeding programmes for ten major vegetable species [114]. The African Orphan Crops Consortium is another important initiative advancing research on African crops, which is committed to developing genomics resources for 57 of the cultivated vegetable species included in this review [115]. Despite numerous important efforts such as these, very low research and conservation for African and Asian vegetables was still detected in this study, which is likely due to the vast diversity of vegetables available in these regions (406 species of vegetable in Asian Pacific Region and 165 species in Africa). Significant time, investments and policy support will be necessary to advance research, breeding, and promotion for neglected vegetables in these mega-diverse biodiversity regions, which could in turn be valuable for enabling transformations toward more nutrition sensitive agriculture.

We acknowledge that the number of Google Scholar records may not be a perfect indicator of research effort because this index cannot possibly capture all the studies that have been carried out for every species. The results were consistent with expectations that globally important crops (e.g., tomato, eggplant, cucumber, and lettuce) would have a much higher number of records compared to less common and more poorly known species, which supports the validity of this measure as an indicator of research effort. Additional indicators of research effort, such as investments in research programmes and training of researchers on specific species would have been interesting to include in the study but this information is challenging to access in a consistent and comprehensive form for global level analyses. The Agricultural Research and Development Indicators (ASTI) reveal relatively low investments in vegetables as compared to other crops and commodities in many countries (e.g., Guatemala 13% of research focused on potatoes [116]; India 8% of research focused on vegetables [117]; Mali 6% of research focused on horticultural crops [118]) but very little detail is provided in these statistics about specific crop species. Coverage in FAOSTAT is similarly not a perfect indicator of knowledge on species distribution and production levels. Much more detailed information is certainly available on the distribution and production of some species in some locations. However, accessing this data in a consistent and exhaustive form suitable for global level analyses would be very difficult. As FAOSTAT presents a standard for agricultural production statistics and is frequently relied upon by the agricultural research community for analyses of global production, we see a great value in this indicator for reflecting the level of accessible knowledge on these species. Our results highlight many gaps in the database and some peculiarities, such as higher coverage of geophytes and herbaceous phanerophytes compared to other groups that results mainly from the high number of species captured under common name categories like "yams" (20 species) or "Plantains and others" (five species). Documentation of vegetables should be vastly improved in FAOSTAT and national production statistics to support their promotion and integration into nutrition-sensitive agricultural and food systems. Disaggregating figures for different species, especially for those that are not closely related taxonomically (e.g., "Carrots and turnips"), would be an important step in this direction.

Poor documentation of production levels, as well as poor availability of data on the nutritional and agronomic characteristics of the cultivated vegetables makes it challenging to assess their use potentials. The nutritional composition of traditional vegetables is patchily documented in national and regional food composition tables [119], while the FAO EcoCrop database was found to cover only 29% of the vegetable species in our review. Among those covered, 50 species are capable of producing on low quality soil with 300 mm of rain or less annually (Table S6). These species may be relevant for supporting vegetable production in marginal areas facing climate change, however it is noted that the remaining 71% of species that are not included in this database should not be overlooked for this role, as they may also have these potentials. In this sense, generating and increasing access to information on the diversity of vegetable species can be vital toward recognizing and leveraging the potentials of cultivated vegetable species.

Many of the 1097 vegetables included in this study are neglected by research, conservation and production statistics but they may not necessarily be underutilized. Some neglected vegetable species may be popularly used in local food systems. Meanwhile others may have important limitations of toxicity, difficult processing, poor productivity, restricted growing ranges, or other constraints that could challenge efforts to promote their use [64]. For example, some of the vegetable species in our review are famine foods (e.g., *Morinda citrifolia* L., *Dioscorea sansibarensis* Pax, and *Icacina oliviformis* (Poir.) J.Raynal), which are consumed mainly in times of food shortage and have toxins that can cause unpleasant side effects such as gastrointestinal complications, demanding intensive processing to render them edible [120]. Increased research attention can help overcome key production, processing and marketing constraints to unlock their benefits for nutrition and incomes [121]. For example, traditional methods and new technologies for food processing can eradicate or reduce toxicity and antinutrients [122,123]. Breeding could also have a role in targeting changes to secondary metabolites to improve acceptability [124]. Overcoming production, processing and marketing challenges to achieve a more substantial and commercially-oriented production may not be feasible for all vegetables and may also not be efficient when alternative crops with better production and market values are available. Many of the neglected cultivated vegetables, such as those used as famine foods, may still have important roles as part of diversified landscapes and regional food systems for strengthening food security, resilience, and nutrition through all seasons and climate conditions.

Trees and shrubs that provide vegetable uses were noted in the review to have received lower attention from research and conservation compared to annual crops. These species may be highly relevant, however, for enhancing availability of nutritious foods while supporting climate change adaptation and mitigation [125,126]. Agroforestry has strong capacity for carbon sequestration and can also stabilize production in wetter and drier years thanks to the positive effects of trees on water infiltration and retention, their deep roots, and provision of alternative sources of food and income [125,127]. Agroforestry moreover provides a number of other ecosystem services, such as windbreaks, shade, structural support, fodder, and improvement of soil fertility, that reinforce farm system sustainability [128–130]. Integrating more trees into agricultural landscapes is being promoted as a climate change adaptation strategy and we note that trees and shrubs with vegetable uses could be a great fit within these approaches, while deserving greater research attention to define best practices. Previous reviews of cultivated vegetables have excluded trees and woody shrubs [70,71]. By including the woody species in this study, we propose an expanded perception of vegetables, while recognizing the potentially critical role that vegetable-providing trees and shrubs could have in climate resilient and nutrition-sensitive agroforestry systems.

This study highlights the large diversity of vegetable species that exist worldwide but it should be acknowledged that the diversity of vegetables is even greater than captured in this review. The intraspecific diversity of cultivated vegetables and the plethora of wild collected vegetables have been excluded for limitations of time and the difficulty of accessing this information. Algae and mushrooms were also excluded from the review, which include a large number of species with vegetable uses. The excluded vegetable diversity also has strategic roles for supporting more nutritious and sustainable food and farm systems and should not be overlooked. Some vegetable species have a tremendous intraspecific diversity, such as *Brassica oleracea* L. which includes important and distinct varieties such as cabbages, broccoli, cauliflower, kales, kohlrabi, collard greens, and Brussels sprouts. Different varieties can present unique tastes and features that are of tremendous cultural and culinary value and of increasing interest for marketing and improving nutrition [131,132]. Wild vegetables are also an integral and diverse component of traditional agricultural systems that continue to form a significant proportion of the global food basket [133–137]. Many wild vegetables have higher mineral and vitamin contents than cultivated vegetables [134,138,139]. In addition to these conscious exclusions from the database, it is also possible that some cultivated vegetable species have unintentionally been excluded. The species list in the Mansfeld Encyclopedia is comprehensive but it is also an evolving resource that has expanded considerably in its coverage since the first and second editions as a result of dedicated research attention and because new species have been coming into cultivation through innovations in previous decades [66].

5. Conclusions

Despite some gaps and limitations, this review has provided a good reflection of the diversity of cultivated vegetable species worldwide and trends for their research, conservation, and documentation. The study revealed that vegetables from Africa and the Asia-Pacific region have received less attention from research, conservation and production statistics as compared to vegetables from other regions, which is a gap that could be closed to leverage the role of traditional vegetables in more nutrition-sensitive agriculture in these regions. Vegetables with growth forms other than therophytes (annual plants), including many trees and shrubs with edible leaves, are largely neglected by research and conservation but merit attention to leverage their roles in agroforestry systems which can enable more sustainable vegetable production under climate change. Creating an enabling policy environment is ultimately critical for mainstreaming the use of a wider diversity of vegetables in research and development programs. Supportive policies are needed to advance research, ex situ conservation, and documentation of these species. Given the high reliance of most cultivated vegetables on in situ/on farm conservation, improving formal and informal seed systems and dissemination of relevant information to farmers (especially on cultivation requirements, resilience and nutritional benefits), strengthening the role of custodian farmers and community seed banks, increasing consumer awareness, and upgrading local value chains to encourage production are critical actions to ensure continued use and maintenance of these resources into the future. While not all 1097 cultivated vegetable species included in this study may have potential for more widespread or intensive promotion, many could have more important roles in nutrition-sensitive local production and food systems with greater attention to study, document, conserve, and promote their roles.

Supplementary Materials: The following are available online at http://www.mdpi.com/2077-0472/8/7/112/s1, Table S1: Typology of the regions of origin of cultivated vegetable species, Table S2: Cultivated vegetable species with very limited research attention related to food, vegetable or nutrition applications (1 to 10 Google scholar records), Table S3: Cultivated vegetable species with no accessions in ex situ collections, Table S4: Cultivated vegetable species with production data included and possibly included in FAOSTAT, Table S5: Cultivated vegetable species with substantial coverage by research, ex situ conservation, and production data, Table S6: Cultivated vegetable species documented in EcoCrop with capacity to produce on low quality soils with 300 mm of rain or less, Database S1: Cultivated vegetable species of the world documented in the Mansfeld Encyclopedia and their uses, growth forms and regions of origin (.csv).

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