



Essay

Domesticating the Undomesticated for Global Food and Nutritional Security: Four Steps

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Abstract: Ensuring the food and nutritional demand of the ever-growing human population is a major sustainability challenge for humanity in this Anthropocene. The cultivation of climate resilient, adaptive and underutilized wild crops along with modern crop varieties is proposed as an innovative strategy for managing future agricultural production under the changing environmental conditions. Such underutilized and neglected wild crops have been recently projected by the Food and Agricultural Organization of the United Nations as ‘future smart crops’ as they are not only hardy, and resilient to changing climatic conditions, but also rich in nutrients. They need only minimal care and input, and therefore, they can be easily grown in degraded and nutrient-poor soil also. Moreover, they can be used for improving the adaptive traits of modern crops. The contribution of such neglected, and underutilized crops and their wild relatives to global food production is estimated to be around 115–120 billion US\$ per annum. Therefore, the exploitation of such lesser utilized and yet to be used wild crops is highly significant for climate resilient agriculture and thereby providing a good quality of life to one and all. Here we provide four steps, namely: (i) exploring the unexplored, (ii) refining the unrefined traits, (iii) cultivating the uncultivated, and (iv) popularizing the unpopular for the sustainable utilization of such wild crops as a resilient strategy for ensuring food and nutritional security and also urge the timely adoption of suitable frameworks for the large-scale exploitation of such wild species for achieving the UN Sustainable Development Goals.

Keywords: anthropocene; climate resilient; food and nutritional security; resource conservation; underutilized crops; Sustainable Development Goals

1. Producing More with Less Resources: The Need of the Hour

The sustainable utilization of our limited natural resources for maximizing the food production [1] within the planetary boundaries [2] is a serious challenge for attaining the United Nations Sustainable Development Goals (UN-SDGs), especially the first, second and third goals namely (i) no poverty, (ii) zero hunger and (iii) good health and wellbeing. Since the indiscriminate usage of a critical resource governing agricultural production, i.e., N, has already crossed planetary boundaries [2], there is a growing concern regarding the cultivation of high-input demanding modern crop varieties under resource-poor conditions. Moreover, the quality and availability of two other inputs vital for agricultural production, i.e., water and land, are already in a thinning state [3,4]. The changing climatic condition is another impediment for food production as it negatively affects the quality and availability of the critical resources as well as the quality and quantity of the agricultural production itself [5]. Since we have to enhance the food production by 70% for meeting the demand of the growing population in 2050, the cultivation of resilient, nutritionally rich, and low-resource intensive crops are of paramount importance for human wellbeing and environmental sustainability [6]. In this context, [7,8] the domestication of undomesticated, wild and neglected crops and exploiting their natural traits to

efficiently use critical natural resources such as N, P, water, and land offers huge promise in attaining future food security as they are bestowed with high nutritional value [9,10] and adaptive traits [11]. Importantly, they need only minimal input and care so they can be easily cultivated in marginal and other nutrient-poor soil and even under changing climatic conditions [11]. Here we propose four important steps, i.e., (i) exploring the unexplored, (ii) refining the unrefined traits, (iii) cultivating the uncultivated, and (iv) popularizing the unpopular for the large-scale exploitation of such important but still underutilized and neglected crops for global food and nutritional security (Figure 1).

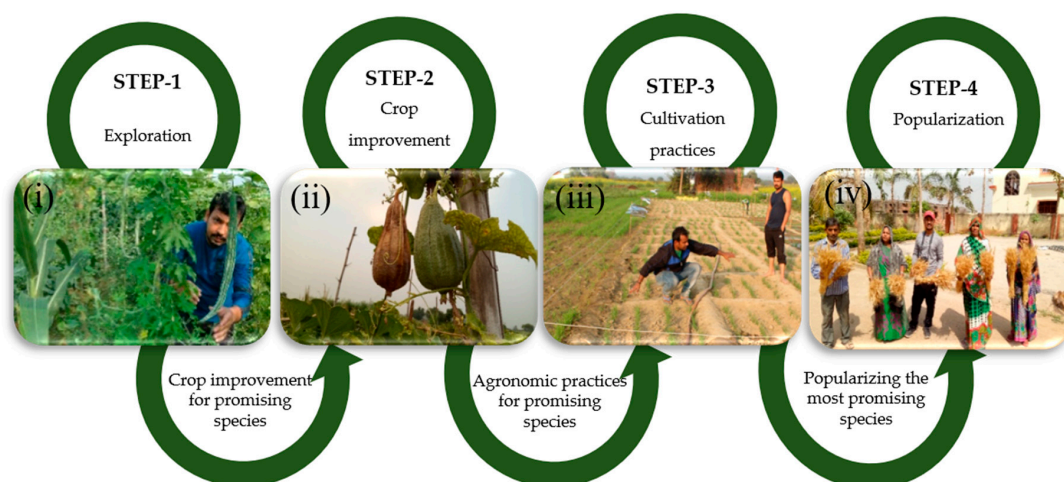


Figure 1. A casual loop diagram showing various steps involved in the sustainable utilization of wild and neglected crops for global food and nutritional security. (i) Step-1: exploration of various kind of wild and neglected crops; (ii) Step-2: improving the desirable traits in promising species by conventional as well as modern biotechnological approaches; (iii) Step-3: standardization and optimization of various agronomic practices for their large-scale exploitation and (iv) Step-4: the popularization of unpopular crops among farmers, policy makers, and other stakeholders.

2. Exploring the Unexplored: First Step

A list of nutritionally relevant, neglected and wild crops for global food security [10–14] is given in Table 1. While it has been reported that about 5538 crops have been used for food by humans throughout the history, only 12 crops contribute the lion share of the current global food production [12,15]. Among this, three crops namely rice, wheat and maize account for >50% the world's calories [15]. Though there are few estimates regarding the number of underutilized species (for example, Arora (2014) reported 992 species across the world), still a majority of them are unknown to various stakeholders. Therefore, the detailed exploration of such species from various agro-climatic regions of the world is important for identifying the promising species (Figure 2) like cereals/pseudo-cereals, roots and tubers, pulses, fruits and vegetables, nuts, seeds and spices etc. and their successful utilization in a dietary diversification program [9,15–17]. For this, a well-coordinated wild crop exploration program at various scales (i.e., national, regional, and global) are imperative. For example, Food and Agricultural Organization (FAO) has recently started an initiative to identify the Future Smart Food (FSF) crops on a regional basis and have identified 39 nutrition-sensitive and climate resilient crops from South and South East Asia as FSF [13] with the consultation of national experts from Bangladesh, Bhutan, Cambodia, India, Lao PDR, Myanmar, Nepal and Vietnam. While they proposed nine species of cereals/pseudo-cereals (buckwheat, tartary buckwheat, foxtail millet, porso millet, sorghum, amaranth, grain amaranth, quinoa, and specialty rice), six species of roots and tubers (taro, swamp taro, purple yam, fancy yam, elephants foot yam, and sweet potato), nine species of pulses (grasspea, fababean, cowpea, mungbean, blackbean, ricebean, lentil, horsebean, and soybean), 9 species of fruits and vegetables (drumstick, chayote, fenugreek, snake gourd, pumpkin, roselle, Indian gooseberry, jackfruit and wood apple), and five species of nuts, seeds and spices (linseed, walnut, Nepali butter tree, perilla and Nepali

pepper) as FSFs for the South and South East Asia region [13] for further exploitation, there are many more neglected and wild species to be included and projected as FSFs (Figure 3A,B). For an instance, a detailed survey conducted by authors during the last few years in India (Figure 3) has revealed that there are many potential FSF such as finger millet, kodo millet, little millet (cereals/pseudo-cereals), air potato, turnip, kohlrabi, kudzu (roots and tubers), winged bean, sword bean, pigeon pea, chick pea (pulses), spine gourd, clove bean, phalsa, custard apple, kadamba, chenopodium, brown mustard, water spinach, jujube, ground cherry (fruits and vegetables) [10] etc. to be included in the regional list and thereby encouraged to be exploited them for future food security (for more such species, please see Figure 3A and Table 1). The cultivation of such species are not only important for global food security but also for attaining many other UN-SDGs (Figure 3B).



Figure 2. Exploration and germplasm collection of wild crops from diverse habitat ((a–e) collection from farmer’s field, backyard and kitchen garden; (f) pond) is essential for identifying most promising species.

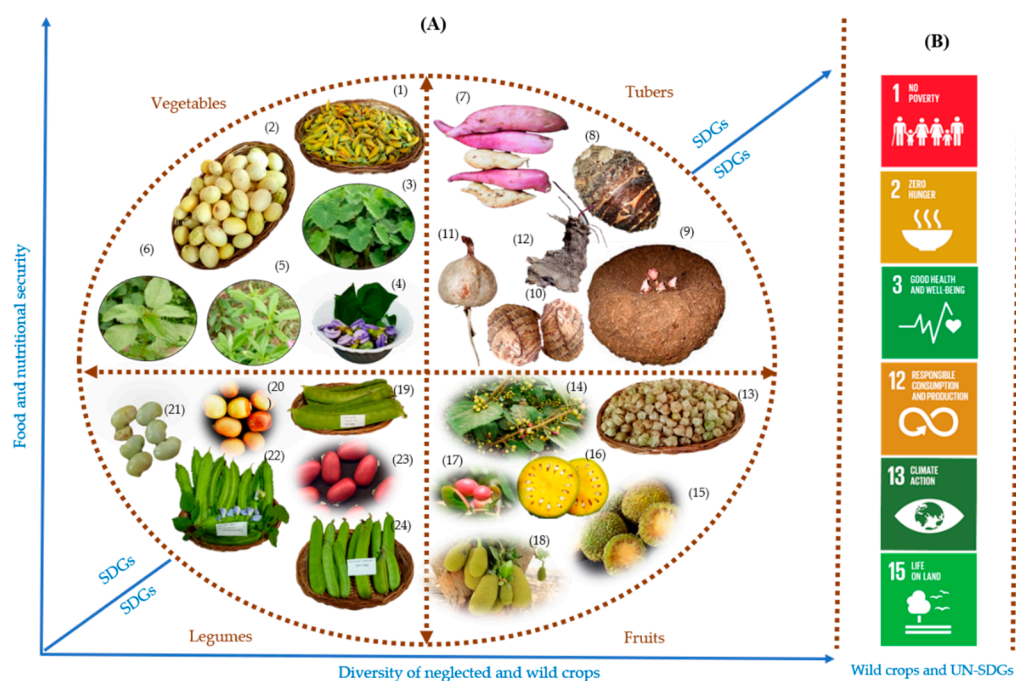


Figure 3. Schematic representation of the inter-relationship between diversity of wild and neglected crops, food and nutritional security and UN-SDGs. (A) food and nutritional security increases with the

large-scale exploitation of neglected and wild crops. Circle shows various neglected wild species: (1) Indian hemp (*Crotalaria juncea*); (2) Tarali (*Melothria heterophylla*); (3) Taro (*Colocasia esculenta*); (4) Flower and leaves of Winged bean (*Psophocarpus tetragonolobus*); (5) Water leaf (*Talinum fruticosum*); (6) Indian jute (*Corchorus olitorius*); (7) Wild sweet potato (*Ipomoea batatas*); (8) Elephant's ear (*Colocasia gigantea*); (9) Elephant foot yam (*Amorphophallus paeoniifolius*); (10) Taro (*Colocasia esculenta*); (11) Indian Kudzu (*Pueraria tuberosa*); (12) Tuber of purple yam (*Dioscorea alata*); (13) Winter cherry (*Physalis angulata*); (14) Phalsa (*Grewia asiatica*); (15) Bur flower tree (*Neolamarckia cadamba*); (16) Wood apple (*Aegle marmelos*); (17) Karanda (*Carissa carandas*); (18) Jackfruit (*Artocarpus heterophyllus*); (19) Pods of large sword bean (*Canavalia gladiata*); (20) Seeds of winged bean (*Psophocarpus tetragonolobus*); (21) Seeds of vegetable hummingbird (*Sesbania grandiflora*); (22) Pods of winged bean (*Psophocarpus tetragonolobus*); (23) Seeds of large sword bean (*Canavalia gladiata*); and (24) Sword bean (*Canavalia virosa*) (B) Sustainable utilization of wild and neglected crops are essential for attaining UN-SDGs.

Table 1. An indicative list of promising neglected and underutilized species such as roots and tubers, cereals and pseudo-cereals, fruits and nuts, vegetables, legumes, spices, condiments, and food-dye agents for global food and nutritional security [10–14].

SL No.	Common Name	Scientific Name
(A) Roots and tubers		
1	Yams	<i>Dioscorea spp.</i>
2	Yacon	<i>Smallanthus sonchifolius</i>
3	Ulluco	<i>Ullucus tuberosus</i>
4	Taro	<i>Colocasia esculenta</i>
5	Arracacha	<i>Arracacia xanthorrhiza</i>
6	American yam bean	<i>Pachyrhizus spp</i>
7	Maca	<i>Lepidium meyenii</i>
8	Oca	<i>Oxalis tuberosa</i>
9	Parsnip	<i>Pastinaca sativa</i>
10	Cocoyam	<i>Xanthosoma sagittifolium</i>
11	Elephant foot yam	<i>Amorphophallus paeoniifolius</i>
12	Kohlrabi	<i>Brassica oleracea var. gongylodes L</i>
13	Wild turnip	<i>Brassica rapa var. rapa</i>
14	Eddoe	<i>Colocasia antiquorum</i>
15	Sweet potato	<i>Ipomea batatas</i>
16	Indian lotus	<i>Nelumbo nucifera Gaertn.</i>
17	Country potato	<i>Plectranthus rotundifolius</i>
18	Wild cassava	<i>Manihot spp.</i>
19	Indian Kudzu	<i>Pueraria tuberosa</i>
20	Edible Chlorophytum	<i>Chlorophytum tuberosum</i>
21	Asparagus	<i>Asparagus racemosus</i>
(B) Cereals and pseudo-cereals		
22	Einkorn	<i>Triticum monococcum</i>
23	Emmer	<i>T. dicoccon</i>
24	Spelt	<i>T. spelta</i>
25	Tef	<i>Eragrostis tef</i>

Table 1. Cont.

SL No.	Common Name	Scientific Name
26	Fonio	<i>Digitaria exilis</i>
27	Cañihua	<i>Chenopodium pallidicaule</i>
28	Finger millet	<i>Eleusine coracana</i>
29	Kodo millet	<i>Paspalum scrobiculatum</i>
30	Foxtail millet	<i>Setaria italic</i>
31	Little millet	<i>Panicum sumatrense</i>
32	Proso millet	<i>Panicum miliaceum</i>
33	Amaranth	<i>Amaranthus caudatus</i>
34	Buckwheat	<i>Fagopyrum spp.</i>
35	Job's tears	<i>Coix lacryma-jobi</i>
36	Red amaranth	<i>Amaranthus cruentus L</i>
37	Pearl Millet	<i>Pennisetum glaucum (L.) R.Br.</i>
(C) Fruits and nuts		
38	Maya nut	<i>Brosimum alicastrum</i>
39	Breadfruit	<i>Artocarpus altilis</i>
40	Jackfruit	<i>Artocarpus heterophyllus</i>
41	Wild jackfruit	<i>Artocarpus hirsutus</i>
42	Fox nut	<i>Euryale ferox</i>
43	Baobab	<i>Adansonia digitate</i>
44	Jujube	<i>Ziziphus mauritiana</i>
45	Cherimoya	<i>Annona cherimola</i>
46	Cape gooseberry	<i>Physalis peruviana</i>
47	Naranjilla	<i>Solanum quitoense</i>
48	Pomegranate	<i>Punica granatum</i>
49	Noni	<i>Morinda citrifolia</i>
50	Marula	<i>Sclerocarya birrea</i>
51	Tamarind	<i>Tamarindus indica</i>
52	Annona	<i>Annona spp.</i>
53	Safou	<i>Dacryodes edulis</i>
54	Mangosteen	<i>Garcinia mangostana</i>
55	Salak	<i>Salacca spp.</i>
56	Nipa palm	<i>Nypa fruticans</i>
57	Monkey orange	<i>Strychnos cocculoides</i>
58	Duku	<i>Lansium domesticum</i>
59	Boscia	<i>Boscia spp.</i>
60	Carissa	<i>Carissa edulis</i>
61	Coccinia	<i>Coccinia trilobata</i>
62	Acacia	<i>Acacia toritilis</i>
63	Kei apple	<i>Dovyalis caffra</i>
64	Tree grapes	<i>Lamnea spp.</i>

Table 1. Cont.

SL No.	Common Name	Scientific Name
65	Medlars	<i>Vanguera spp.</i>
66	Pitanga	<i>Eugenia uniflora</i>
67	Malabar chestnut	<i>Pachira aquatica</i>
68	Camu camu	<i>Myrciaria dubia</i>
69	Dragon fruit	<i>Hylocereus spp.</i>
70	Brazil nut	<i>Bertholletia excels</i>
71	Egg nut	<i>Couepia longipendula</i>
72	Quince	<i>Cydonia oblonga</i>
73	Yara Yara	<i>Duguetia lepidota</i>
74	Araza	<i>Eugenia stipitate</i>
75	Lúcuma	<i>Lucuma obovate</i>
76	Miracle fruit	<i>Synsepalum dulcificum</i>
77	Water chestnut	<i>Trapa natans</i>
78	Indian bael	<i>Aegle marmelos</i>
79	Chilean wineberry	<i>Aristotelia chilensis (Molina)</i>
80	Lakoocha	<i>Artocarpus lacucha</i>
81	Karanda	<i>Carissa carandas</i>
82	Assyrian plum	<i>Cordia myxa</i>
83	Cluster Fig	<i>Ficus racemosa</i>
84	Phalsa	<i>Grewia asiatica</i>
85	Wood-apple	<i>Limonia acidissima L.</i>
86	Mulberries	<i>Morus alba</i>
87	Burflower-tree	<i>Neolamarckia cadamba</i>
88	Indian Gooseberry	<i>Phyllanthus emblica</i>
89	Angular winter cherry	<i>Physalis angulata</i>
90	Manila tamarind	<i>Pithecellobium dulce (Roxb.) Benth.</i>
91	Black nightshade	<i>Solanum nigrum L.</i>
92	Indian almond	<i>Terminalia catappa L.</i>
93	Jujube	<i>Ziziphus jujube</i>
94	Mahua	<i>Madhuca longifolia</i>
95	Hog Plum	<i>Spondias dulcis</i>
96	Starfruit	<i>Averrhoa carambola</i>
97	Bilimbi	<i>Averrhoa bilimbi</i>
98	Indian coffee plum	<i>Flacourtia jangomas</i>
99	Common guava	<i>Psidium guajava</i>
100	Soursop	<i>Annona muricata</i>
101	Spring Asparagus	<i>Asparagus officinalis</i>
102	Wild pear	<i>Pyrus communis</i>
103	Hill lemon	<i>Citrus psedolimon</i>

Table 1. Cont.

SL No.	Common Name	Scientific Name
(D) Vegetables		
104	Moringa	<i>Moringa oleifera</i>
105	African eggplant	<i>Solanum aethiopicum</i>
106	Thorny amaranth	<i>Amaranthus spinosa</i>
107	Wild amaranth	<i>Amranthus viridis</i>
108	Brassica	<i>Brassica rapa</i> varieties
109	Locust bean	<i>Parkia biglobosa</i>
110	Chayote	<i>Sechium edule</i>
111	Chrysanthemum	<i>Chrysanthemum oronarium</i>
112	Bitter gourd	<i>Momordica charantia</i>
113	Angle gourd	<i>Luffa acutangula</i>
114	Snake gourd	<i>Thrichosantes cucumerina</i> var. <i>anguina</i>
115	Indian spinach	<i>Basella rubra</i> , <i>Basella alba</i>
116	Spider plant	<i>Cleome gynandra</i>
117	Jute	<i>Corchorus olitorius</i>
118	Black nightshade	<i>Solanum nigrum</i>
119	Ivy gourd	<i>Coccinia grandis</i>
120	Gourd	<i>Lagenaria siceraria</i>
121	Celosia	<i>Celosia argentea</i>
122	Dika	<i>Irvingia</i> spp.
123	Egusi	<i>Citrullus lanatus</i>
124	Marama	<i>Tylosema esculentum</i>
125	Shea butter	<i>Vitellaria paradoxa</i>
126	Giant swamp taro	<i>Cyrtosperma merkusii</i>
127	Akoub	<i>Gundelia tournefortii</i>
128	Crambe	<i>Crambe</i> spp.
129	Cardoon	<i>Cynara cardunculus</i>
130	Eru	<i>Gnetum africanum</i>
131	Purslane	<i>Portulaca oleracea</i>
132	Golden thistle	<i>Scolymus hispanicus</i>
133	Bitter leaf	<i>Vernonia amygdalina</i>
134	Cabbage Leaf Mustard	<i>Brassica juncea</i> var. <i>rugosa</i>
135	Pigweed	<i>Chenopodium album</i>
136	Asian spiderflower	<i>Cleome viscosa</i>
137	False Amaranth	<i>Digera muricate</i> (L.) Mart.
138	Water spinach	<i>Ipomoea aquatica</i>
139	Thumbai	<i>Leucas aspera</i> (Willd.) Linn
140	Sweet neem	<i>Murraya koenigii</i>
141	Sickle Senna	<i>Senna tora</i>

Table 1. Cont.

SL No.	Common Name	Scientific Name
142	Waterleaf	<i>Talinum fruticosum</i> (L.) Juss
143	Fenugreek	<i>Trigonella foenum graecum</i>
144	Spiny gourd	<i>Momordica dioica</i> Roxb. Ex Willd.
145	Pointed gourd	<i>Trichosanthes dioica</i> Roxb.
146	Sunn hemp	<i>Crotalaria juncea</i> L.
147	Khejri Tree	<i>Prosopis cineraria</i>
148	Sweet leaf	<i>Sauropus androgynus</i>
149	Water spinach	<i>Ipomea aquatica</i>
150	Tarali	<i>Melothria heterophylla</i>
151	Kuda	<i>Holarrhena pubescens</i>
152	Korla	<i>Bauhinia malabarica</i>
153	Kawla	<i>Smithia hirsuta</i>
154	Dragon stalk yam	<i>Amorphophallus commutatus</i>
155	Bamboo	<i>Dendrocalamus strictus</i>
156	Wild senna	<i>Senna tora</i>
157	Dinda	<i>Leea indica</i>
158	Bharangi	<i>Rothea serrata</i>
159	Edible fern	<i>Diplazium esculentum</i>
(E) Legumes		
160	Mungbean	<i>Vigna radiata</i>
161	Adzuki bean	<i>V. angularis</i>
162	Ricebean	<i>V. umbellata</i>
163	Lupin	<i>Lupinus mutabilis</i>
164	Bambara groundnut	<i>Vigna subterranean</i>
165	Jack bean	<i>Canavalia ensiformis</i>
166	Grasspea	<i>Lathyrus sativus</i>
167	Lablab	<i>Lablab purpureus</i>
168	Pigeon pea	<i>Cajanus cajan</i>
169	African yam bean	<i>Sphenostylis stenocarpa</i>
170	Kersting's groundnut	<i>Macrotyloma geocarpum</i>
171	Sword bean	<i>Canavalia gladiata</i>
172	Jack bean	<i>Canavalia virosa</i>
173	Winged bean	<i>Psophocarpus tetragonolobus</i>
174	Cluster bean	<i>Cyamopsis tetragonoloba</i> (L.) Taub
175	Agati	<i>Sesbania grandiflora</i> (L.) Pers.
176	Broad bean	<i>Vicia faba</i>
177	Chickpea	<i>Cicer arietinum</i>
178	Peanut	<i>Arachis hypogea</i>
179	Black gram	<i>Vigna mungo</i>
180	Black lentil	<i>Lens culinaris</i>

Table 1. Cont.

SL No.	Common Name	Scientific Name
(F) Spices, condiments, food-dye agents		
181	Makoni	<i>Fadogia ancylantha</i>
182	Annatto	<i>Bixa orellana</i>
183	Mustard seed	<i>Brassica juncea</i>
184	Fenugreek	<i>Trigonella foenumgraecum</i>
185	Pandan	<i>Pandanus amaryllifolius</i>
186	Polygonum	<i>Polygonum odoratum</i>
187	Antidesma	<i>Antidesma venosum</i>
188	Uer	<i>Lippia carviadora</i>
189	Rocket	<i>Diplotaxis spp</i>
190	Caper	<i>Capparis spinosa</i>
191	Monkey cola	<i>Cola lateritia</i>
192	Sea buckthorn	<i>Hippophae rhamnoides</i>
193	Nigella	<i>Nigella sativa</i>
194	Culantro	<i>Eryngium foetidum</i>
195	Coriander	<i>Coriandrum sativum</i>
196	Wild chilies	<i>Capsicum spp.</i>

The application of biotechnological advances for exploring crop diversity like genotyping by sequencing, genotyping arrays, and pangenomics approaches [18] is another important strategy for assessing genetic diversity. Crop genome sequencing can provide insight into genetic variation through the re-sequencing [19]. Jiao et al. (2012) re-sequenced 278 elite maize lines (USA and Chinese maize lines) and identified >27 million single-nucleotide polymorphisms (SNPs). Similarly, the 3000-rice genome project resulted in the identification of >18.9 million SNPs [20,21] and the methylation-sensitive digestion of genomic DNA coupled with next-generation sequencing in wheat resulted in ~23,500 SNPs [22]. Furthermore, whole-genome re-sequencing was also done for barley [23], soybean [24], and lupin [25].

However, whole-genome sequencing is yet to be done in many promising but neglected crops and there are many wild species yet to be explored for their food and nutritional significance. For example, exploring the diversity in root and tuber crops are essential for the food security, especially in tropical regions as they are nutritionally rich and widely found in tropical regions [26]. *Vigna* is another important legume genus having more than a 100 species of high nutritional value for human and animal consumption [27]. Among this, only 10 species have been domesticated so far and the potential of the rest of the remaining 90 species is yet to be explored. Prickly pear (*Opuntia* spp.) is another valuable fruit crop for the semi-arid regions [28]. Similarly, Indian spinach or Malabar spinach (*Basella* species), is a resilient, nutritionally significant, perennial leafy vegetable native to tropical region [11]. However, as in the case of many other tropical leafy vegetables such as wild amaranth [10], water spinach, and waterleaf etc., *Basella* species are yet to be exploited for the dietary diversification program and food security [11]. Therefore, the large-scale exploration of underutilized and neglected crop species from various agro-climatic regions of the world, with the active involvements of the Consultative Group on International Agricultural Research (CGIAR) institutions, Crop Trust, local and national institutions, and with the financial support from Food and Agricultural Organization of the United Nations (UN-FAO), corporate bodies (through corporate social responsibility), Non-Governmental

Organizations (NGOs), and also from concerned national governments, are imperative for exploring the most promising species as well as identifying the current diversity of such wild species.

Applications of geoinformatics tools such as remote sensing and geographical information system (RS & GISs) can be used for mapping the distribution of neglected and wild crops [29] in various agro-climatic regions of the world, as well as modelling their habitat suitability for identifying the most suitable areas for large-scale cultivation [17,30]. Apart from the large-scale exploration of neglected and underutilized species from diverse habitats and agroecological zones of the world, the conservation of promising species is also equally important for facilitating their future utilization [6,14]. The exploitation of indigenous and local knowledge (ILK) along with the successful incorporation of the biocultural practices of the local people are very much essential for applying the traditional mode of conservation (Figure 4), whereas the exploitation of modern techniques for germplasm storage is also essential for maintaining such vital resources for the future use [13,14]. Creating community gene banks at farmer's fields is an excellent strategy for the long-term conservation of such underutilized species (Figure 5).



Figure 4. Apart from the exploration of wild and neglected crops, conservation of the germplasms of most promising species are also equally important for their sustainable utilization. For this, a blend of traditional (a–c) as well as modern (d,e) germplasm storage technologies should be adopted.



Figure 5. Field gene bank for conservation of neglected and underutilized crops. Maintaining germplasms of promising species at farmer's field itself is a promising strategy for conservation. Figures shows the cultivation of wheat in the farmer's field of Rajgarh, Mirzapur district, UP, India.

3. Refining the Unrefined Traits: Second Step

While modern agriculture aiming for higher productions prefers new cultivars that are developed through selection and fixation of favorable alleles providing most desirable traits, unscientific practices coupled with due negligence results in loss of wild or traditional crops and crop varieties and thereby causing genetic erosion and decline in landraces and ecotypes [31]. Therefore, once the promising wild and neglected species have been identified, developing a suitable crop improvement program for traiting or featuring desirable traits is another major strategy. Though most of the wild species are endowed with many positive traits such as stress tolerance (drought, flood, salinity, heat, pest and diseases, etc.) and able to grow even in resource-poor conditions [5,7,9], these attributes can be further refined by crop improvement by using next generation sequencing (NGS) for genomic selection [32], the identification of candidate loci using quantitative trait locus (QTL) analyses, targeted gene replacement using zinc-finger nucleases and transcription activator-like effector nucleases and also by using clustered regularly interspaced short palindromic repeats (CRISPR/Cas system) etc. [18,33–36].

The application of genomic technologies [37] was found to increase the productivity of several orphan crops such as cassava, sweet potato, coconut, sorghum, yam, groundnut, common bean, chickpea, cowpea, cacao etc. [18], especially, exploring plant microRNAs (miRNAs) for developing climate resilient crops [38]. Khan et al. (2019) proposed the application of CRISPR-Cas9 for engineering the domestication traits in wild tomato for higher nutritive value and better adaptation to multiple stresses [39]. Pigeon pea (*Cajanus cajan*) is another versatile, stress tolerant and nutritious grain legume for enhancing the sustainability of dry tropical and sub-tropical system [40] and therefore, the crop

breeding programs in pigeon pea has resulted in enhancing its tolerance to heat, cold, drought and waterlogging [40]. Muthamilarasan et al. (2016) explored the application of omics technologies for exploring suitable millet models for developing nutrient rich graminaceous crops [41]. De novo sequencing and comparative leaf transcriptome analysis of underutilized winged bean (*Psophocarpus tetragonolobus* (L.) DC) has been done by Singh et al. (2017) for removing the anti-nutritional factors in winged bean like condensed tannin (CT) and proanthocyanidin (PA) [42]. Such transcriptomic insights can be used for removing the antinutritional factors (high tannin and lignin content) in sword bean also. Lemmon et al. (2018) enhanced the domestication traits in an orphan crop of Solanaceae (groundcherry) by gene editing [36]. While biotechnological advances have revolutionized the crop breeding domain, there are many other potential species yet to be considered for crop breeding for improving their nutritional and domestication traits [10].

Apart from modern breeding programs, the exploitation of conventional breeding techniques [43,44] is also important for improving the traits as well as economic benefits of such underutilized species [43–50]. For instances, the traditional crop improvement techniques like mass selection, pure-line selection, pedigree method, bulk method, backcross method, single seed descent (SSD) method [43,49], mutation breeding [50] etc. are also essential for (i) improving the yield and quality attributing traits of the wild species, (ii) conferring resistance to biotic and abiotic stresses, (iii) enabling better adaptation by altering the crop duration, maturity/earliness etc., (iv) reducing the anti-nutritional factors, (v) enhancing the non-shattering characteristics, and (vi) improving the adaptation range as well as the photo and thermo sensitivity [43].

Targeted and participatory crop breeding programs [46,47] are necessary for some of the underutilized and neglected species such as Indian hemp (*Crotalaria juncea*), tarali (*Melothria heterophylla*), water leaf (*Talinum fruticosum*), Indian jute (*Corchorus olitorius*), Indian kudzu (*Pueraria tuberosa*), winter cherry (*Physalis angulata*), phalsa (*Grewia asiatica*), bur flower tree (*Neolamarckia cadamba*), wood apple (*Aegle marmelos*), jack bean (*Canavalia ensiformis*) etc. For this, a globally coordinated wild crop breeding program (including both conventional as well as modern breeding) under the leadership of CGIAR institutes and various national agricultural organizations is essential for improving the traits of potential lesser utilized species and to bring them to mainstream agriculture.

4. Cultivating the Uncultivated: Third Step

As opined by Massawe et al. (2016), neglected and underutilized wild species are a treasure trove for food security [51]. However, majority of such lesser known species are undomesticated, and therefore, farmers are not aware of their cultivation and propagation methods. Therefore, standardizing the agronomic practices (Figure 6) for such uncultivated edible crops is another major step for optimizing their resource use and also for improving the yield and nutritional quality [7].



Figure 6. Optimization of agronomic practices and mass multiplication strategies are essential for the large-scale exploitation of underutilized crops. Photographs (a–e) shows the various stages of the mass propagation and cultivation of Indian spinach (*Basella alba* and *Basella rubra*).

Though the cultivation practices have been optimized for some of the wild species (for example, pigeon pea [40]; wild rocket [52]; terracrepolo [53]; *Physalis* sp. [54] etc.), such practices are yet to be standardized for a majority of the neglected species. For example, *Basella alba* and *Basella rubra* (Malabar spinach) are two of the highly nutritive, perennial leafy vegetable, capable of growing in diverse kind of habitat (including degraded and disturbed lands), there is no standardized protocols available for the large-scale cultivation of *Basella* sp. through stem cutting [11]. Similarly, there are many underutilized species yet to be introduced into farmers' fields (Figure 3A) and many optimal agronomic practices for improving their domestication traits. Moreover, the standardization of inventive agronomic practices is important for emission reduction [55] while increasing the soil's carbon pool [56,57].

Apart from validating the cultivation practices, standardization of suitable cropping models is also essential for successful crop diversification program. Since a majority of the wild crops are hardy and resilient to diverse climatic conditions, they can be used as border crops, as crop breaks, intercrops and also for multi-cropping and integrated farming practices [58]. Importantly, the cultivation of such wild

crops will result in species diversification through multiple cropping and niche compartmentalization and thereby diversify the ecosystem functions and services [57]. Though monocropping system possess only limited traits to perform critical ecosystem functions (e.g., biological pest control, managing GHG emissions etc.), diversified cropping system have multiple traits to perform mosaic of functions (e.g., nutrient recycling, nitrogen fixation etc.) [56,59]. Moreover, crop diversification is also essential to ensure pollinator diversity such as honey bees, flies, beetles, moths, butterflies, wasps, ants, birds, and bats etc. as they are crucial for agrobiodiversity and other ecosystem services [60]. Therefore, internationally coordinated efforts are imperative to standardizing the cultivation practices of wild crops as well as for conducting their multi-locational trials in the various agro-climatic regions of the world, and such efforts must be linked to the concerned SDG targets of the appropriate national, regional, and international agencies for global sustainable development.

5. Popularizing the Unpopular: Final Step

Last, but not least, popularizing lesser known species as a climate resilient strategy for food security and resource conservation as well as promoting their role in maintaining ecosystem complexity to common people is another important step for their large-scale cultivation. For this, well-coordinated popularization efforts at various levels and scales are essential with the involvement of multiple stakeholders such as NGOs, State Governments, Local Help Groups, farming communities, National Science Academies, the FAO, CGIAR and other UN organizations. (Figures 7 and 8). Moreover, the standardization of cost-effective and suitable mass multiplication strategies (both micro and macro propagation) [61,62] are important for reducing the cost of the plating materials and also for the large-scale popularization of such neglected and underutilized species because such mass multiplication strategies will make the cultivation of novel crops profitable to farmers.



Figure 7. Popularization of neglected and wild edibles among diverse stakeholders especially women is important for dietary diversification program and thereby attaining food and nutritional security. Photographs shows the various interactive sessions of an awareness workshop on sustainable utilization of wild edibles for the health and well-being of the tribal women conducted by authors group in association with the National Academy of Sciences, India (NASI) and also with the support of Krishak, P.G. College, Rajgarh, Mirzapur.



Figure 8. Periodic meetings and community involvements are essential for the awareness creation among indigenous and local community regarding the use of such neglected and underutilized crops for attaining global goals and also for encouraging them to use such species as an intermittent crop for intercropping and crop diversification in family and kitchen garden.

Harnessing indigenous and local knowledge and associated biocultural practices of the local people is an innovative strategy for conservation as well as popularization programs. Since the cultivation of such underutilized and neglected species will empower the indigenous community [5–7], suitable policies must be framed at the local and regional level to harness the ILK and biocultural practices of the local people for the exploration, large-scale exploitation, and also for developing the participatory crop improvement programs for the extensive utilization of such traditional and underutilized wild varieties for dietary diversification program. Therefore, conducting periodic awareness program for farmers especially women and other marginalized people is important for encouraging the introduction of various underutilized crops in their family and kitchen garden and also for developing suitable models for crop diversification based on such neglected and wild crops.

Developing a comprehensive, integrated and multi-utility database having the complete details of wild, neglected and underutilized crops in multiple languages (such as their origin, distribution, nutritional value, cultivation practices, crop genomics, crop improvement strategies, ecosystem services etc.) is of the utmost importance. Though there are websites and databases for crop wild relatives and wild crops, the content and coverage of them are limited. For example, the website of crop wild relatives only showcases 29 priority crops, listed in the Annex 1 of the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA) (www.cwrdiversity.org). Similarly, the global distribution database of crop wild relatives published by the International Centre for Tropical Agriculture (CIAT) is another venture having the distribution database of crop gene pools of 80 species (www.gbif.org). The crop Wild Relatives Global Portal (www.cropwildrelatives.org) is another joint venture by Bioversity International, United Nations Environment Program (UNEP) and Global Environmental Facility (GEF). The International Legume Database and Information Services (ILDIS) is a promising database for legume species across the world (www.ildis.org). However, as we mentioned earlier, the species coverage in those databases must be expanded beyond the Annexure-1

of the ITPGRFA, and most promising species for global food security, especially from the lesser and underutilized leafy vegetables, wild tubers, wild fruits etc. must be included in the database.

The creation of a national or regional inventory of crop wild relatives is another promising strategy [63,64]. Cultivating wild crops in school gardens and using them for the mid-day meal programs of the developing countries, especially in South East Asia and Africa is another way for popularizing the lesser and under-utilized neglected species [17]. State governments can also play a vital role in encouraging the use of nutritionally rich wild crops. For example, the government of India has proposed nutritionally rich millets as ‘nutrimillets’ and urged for global solidarity in popularizing them by celebrating an international year for millets. As a result, the FAO council approves India’s proposal to celebrate the year 2023 as the International Year of Millets (www.pib.nic.in). Furthermore, the existing 11 gene banks under CGIAR must also go beyond their proposed mandate (i.e., confined to the germplasm collection of a particular crop) and would start collecting germplasms of all uncollected species including wild leafy vegetables, wild vegetables, wild edible flowers, wild fruits, wild tubers etc. for ensuring the current and future food security.

6. Concluding Remarks

Unlocking the real potential of undomesticated and wild crops is imperative for global food and nutritional security and also for attaining many other UN-SDGs. However, targeted crop improvement, domestication as well as cost-effective mass cultivation programs are essential for exploiting their real potential. Therefore, international collaborations under the joint leaderships of FAO and CGIAR institutions, national agriculture institutions and State Governments are essential for the exploration, popularization, as well as the large-scale exploitation of undomesticated crops for ensuring the food and nutritional demand of the global population, and also for communicating their multipurpose benefits to various stakeholders, and framing suitable policies accordingly.

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