

PLANTS FOR SPACE PLANTATIONS

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16 Abstract Criteria for selection of candidate crops for closed life support systems are presented and discussed, and desired characteristics of candidate higher plant crops are given. Carbohydrate crops, which are most suitable, grown worldwide are listed and discussed. The sweet potato, Ipomoea batatas Poir., is shown to meet the criteria to the greatest degree, and the criteria are recommended as suitable for initial evaluation of candidate higher plant crops for such systems.			
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PLANTS FOR SPACE PLANTATIONS

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Mankind has taken only the first steps in the study and conquest of space. The first manned orbital stations have been produced and the first flights of people to the moon have been accomplished. However, it cannot be doubted that complicated problems directly connected with an increase in the stay time of man under unusual, closed spacecraft conditions will soon be solved.

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The problem of the development of partially or completely closed life support systems for crews on a long space journey disturbed K.E. Tsiolkovskiy. Thus, in 1911, he wrote: "As plants on earth absorb impurities and give food in return with their leaves and roots, so can plants we take on a journey work continuously for us."¹

Although the outlines of a life support system with the use of green plants still have not been defined sufficiently distinctly, there is no doubt that it will be complicated, consisting of many functionally interconnected links.

*Numbers in the margin indicate pagination in the foreign text.

¹Tsiolkovskiy, K.E., Zhizn v mezhzvezdnoy srede [Life in the Interstellar Medium], Moscow, 1964.

The theoretical basis of the study and development of life support systems on the biological matter cycle principles was the science of biogeocenoses, the foundations of which were laid by V.N. Sukachev.²

In the biosphere of the earth, by using the radiant energy of the sun, green plants form organic substances by photosynthesis, and they simultaneously give off oxygen and absorb carbon dioxide. Due to these unique "factories," which convert radiant energy into diverse substances, man lives safely on the earth. Under natural conditions, complex interactions of plants and other components of the terrestrial communities, biogeocenoses, take place.

In artificially produced systems for space conditions, the effort can be made to simulate natural biogeocenoses. However, complete reproduction of even the simplest of them is scarcely possible today. Therefore, such systems have to be limited to the inclusion of a minimum number of natural components in the cycle, /106 with simplification and acceleration of their complicated interactions which occur in biogeocenoses, by means of including mechanical components or links. Consequently, in the development of the closed life support systems of permanent space vehicles, the biological problems are closely interwoven with engineering solutions and technological possibilities.³

For a scientifically valid selection of the components of the higher plant link of such a "biological-technical community"

²Dadykin, V.P., "The importance of the biogeocenosis science of V.N. Sukachev in the development of closed systems." Izv. AN SSSR, Ser. biol. 2, (1970).

³Shepelev, Ye.Ya., "Human life support systems in spacecraft cabins based on the biological matter cycle," in the collection Kosmicheskaya biologiya i meditsina [Space Biology and Medicine], Moscow, 1966; Osnovy kosmicheskoy biologii i meditsiny [Foundations of Space Biology and Medicine], Vol. 3, Joint Soviet-American Press, Moscow, 1975.

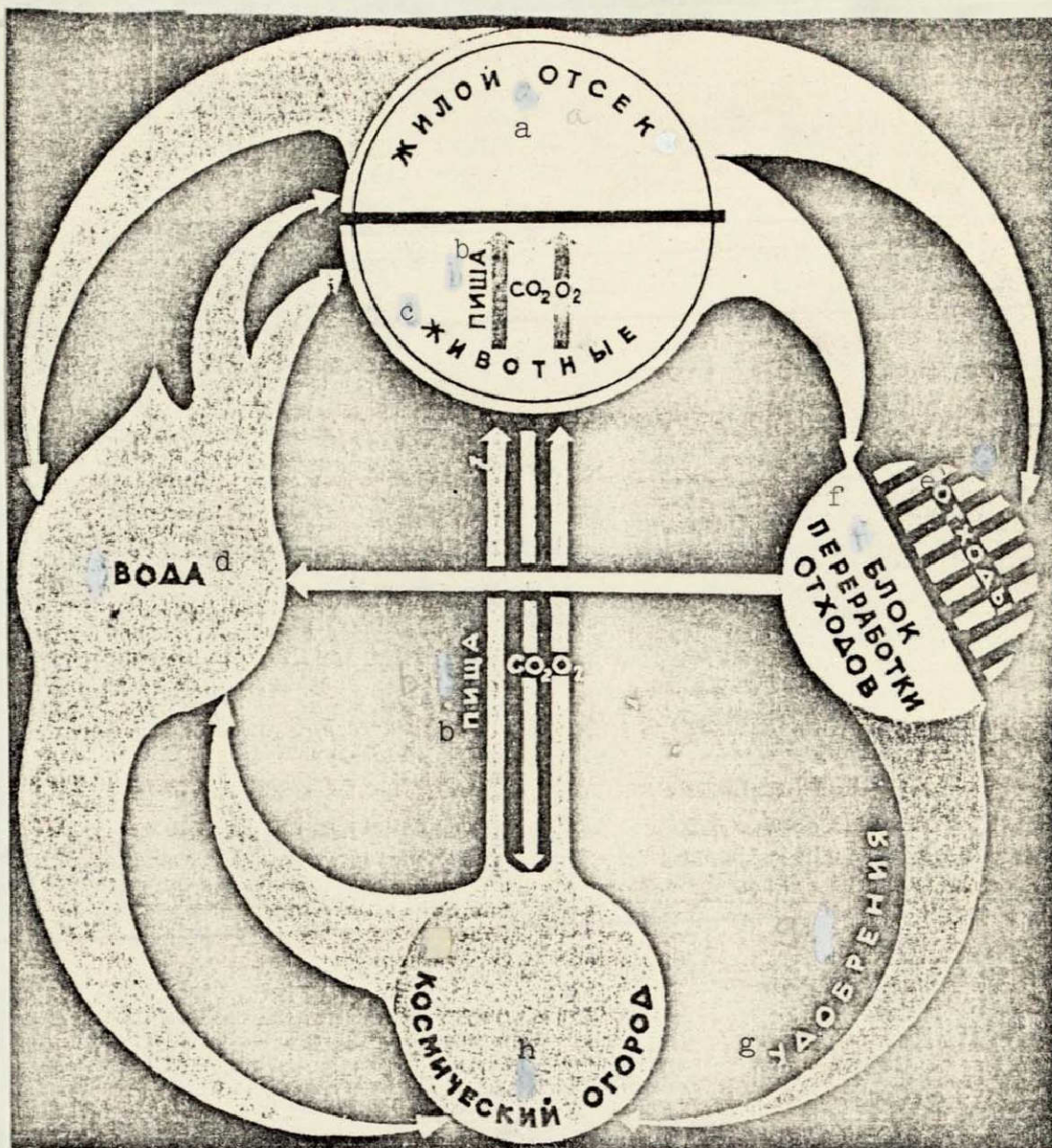


Diagram of hypothetical closed life support system in space; the system includes several functionally connected links; the central link is man with his needs; all remaining links (biological and abiotic) ensure the normal existence of man; animals and plants use food wastes of human vital activities and give him food; plants also participate in regeneration of the atmosphere and, partially, water; abiotic links accelerate the matter cycle, treating part of the wastes and again including them in the biological cycle.

Key: a. Living compartment
b. Food
c. Animals
d. Water

e. Waste
f. Waste treatment unit
g. Fertilizer
h. Space garden

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with specified technical link parameters, complex long-term experiments are necessary.

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However, on the basis of theoretical studies, quite distinct ideas of the principles of selection of agricultural crops for use in these systems have now been formulated. Knowledge of human needs permits the necessary calculations to be carried out, for the synthesis of experimental models of the higher plant links of these systems.

We shall attempt to show one possible way of determination of the structure of the higher plant link of a hypothetical closed life support system. Our approach consists of initial discrimination of the main crop, the supplier of that part of the cosmonaut ration, which takes up the greatest specific weight in normal (earth) human rations and which, with a high degree of probability, can be considered the basis of space rations. This crop should subsequently be the base for building up the remaining plant selection, its output, nutrient and vitamin content, etc., to use for exactly defining the parameters of the mechanical and other links of the system.

As is known, the optimum human ration (including that of a cosmonaut) includes 60-65% carbohydrates, 20-25% fats and 10-15% proteins. The carbohydrates make up the energy base of the ration. With a normal mixed nutrition, they provide about 60% of the standard calorie value of the food, obtained only through the plant part of the ration, 300-600 g per day. Fats fulfill the role of energy reserve of the body. There is 80-150 g of them in the ration, and the biological optimum is considered a combination of 70% animal and 30% plant fats. The proteins make up the basis of the structural elements of the human cells and tissues. A balanced daily cosmonaut ration contains 90-100 g of them, in which 50% of them are proteins of animal origin, since these

include essential amino acids, the content of which in plant proteins is inadequate for full value nutrition. The need of a cosmonaut for vitamins, enzymes, hormones, organic acids, essential oils, antibiotics and mineral salts under normal flight conditions also is almost entirely satisfied by the plant part of the ration.

Thus, the greatest amount of the required human energy is obtained from carbohydrates. Therefore, from the point of view of human food requirements, the main plant component of the links should be a carbohydrate crop.

We now attempt to evaluate the worldwide diversity of carbohydrate crops, from the point of view of their cultivation under small dimension, closed system conditions, and we formulate a certain set of prospective crop selection criteria for this.

The crops used in closed systems should:

be as nutritionally suitable as possible;

give the minimum amount of irreversible wastes (cellulose, tissue);

have the capability of obtaining diverse and full value dishes by simple food preparation technology;

have a sufficiently high output per unit volume in a unit time and reproduce easily and simply;

Be resistant to unfavorable external space flight conditions;

Have acceptable dimensions (small bush, low height) etc);

be compatible with each other and with man, with respect to giving off volatile substances.⁴

All the principles listed are fairly important. Essentially, breeders, plant growers and agronomists follow the majority of them in their work. We adopt this set of criteria as the basis for the conduct of studies, but they are inadequate for determination of the main crop of the higher plant link.

There are other approaches to the selection of plant species for closed systems. Thus, for example, some authors consider that /108 the extent of participation of a species in natural metabolic cycles is not of decisive importance, and that one of the basic indicators of selection should be considered the 'maximum yield' of the required nutrients. In this case, the possibility of the use of such nonagricultural plant species as duckweed or chlorella is considered.⁵ Although distinct successes have been achieved in recent years in the cultivation of lower algae and extraction of full value protein from them, as well as in the utilization of other biological methods of obtaining nutritive materials from nonfood crops, the role of these methods of food production is insufficiently clear. At the same time, it is evident that it still is impossible to solve many problems of nutrition of the crews of prolonged space expeditions this way. Even if the biological value of such nutritive materials is in no way lower than that of the widely used food stuffs, long-term study of the psychological aspects of their use is necessary.

The majority of people usually consider a food ration unacceptable in which, despite the full value of the nutrient composition, accustomed foodstuffs (for example, potatoes) are lacking. The

⁴Dadykin, V.P., Kosmicheskoye rasteniyevodstvo [Space Plant Growing], Moscow, 1968; "Experimental ecological systems including man," in the collection Problemy kosmicheskoy biologii [Problems of Space Biology], Vol. 28, Moscow, 1975.

⁵Wilks, S.S., in Conf. Nutr. Space and Related Waste Problems, Tampa, NASA, 1964, p. 305-310.

acceptability of food consumed, i.e., the subjective taste perception of man towards it can have such a great effect on his physical conditions and on the extent of use of the foodstuffs by him, that it affects his performance. In the development of full value balanced food rations for spacecraft crews, it must be taken into account that food from widely used higher plants are customary and natural.

For plants under sealed cabin conditions, the complete lack of a cycle is important. This is due to the fact that artificial spacecraft cenoses should ensure continuous and uniform production of food, atmosphere and water. An almost stable assimilating surface, the most efficient use of the entire planting area and continuous crop production are the requirements taken into account in development of special continuous (conveyor) plant cultivation procedures. An example of such a green conveyor can be citrus cultivation in the tropics (in distinction from subtropical citrus crops). In a tropical climate, buds, flowers and fruit in various stages of ripeness are found simultaneously on citrus trees.

Thus, it can be considered that plant living conditions in a small closed life support system probably will resemble tropical climate conditions. Constant dark and light periods, temperatures and humidity have to be observed in such a system, and there will be no seasons in it. There will be "perpetual summer?" This means that a prospective crop has to have the biological characteristics of tropical crops.

Evaluation of the environmental conditions of manned cabins has permitted us to refine other characteristics of plants for a space plantation. Thus, for example, many plants have a number of agriculturally useless morphological characteristics, awns, thorns, woody stems, thick leathery membranes, an excess of cellulose, etc. Under closed system conditions, these customary

characteristics on the earth, undesirable for man, acquire an independent, sharply unfavorable importance. In our opinion, their lack has to be a required condition of inclusion of plants in the link. This specifically defines the principle of "having the minimum irreversible wastes." On the basis of this requirement, we do not consider grass crops, which dominate on the earth as suppliers of carbohydrates, as "space" plants, and we prefer the carbohydrate root crops, which are more advantageous for use in space.

Prospective species for use in the higher plant link should be characterized by:

the lack of too narrow temperature "corridors." for growth and development, with temperature requirements for different plant development phases as close together as possible;

the lack of rest periods and prolonged ripening cycles;

the lack of poisons, irritants and other substances (even if they are destroyed by supplementary treatment);

the possibility of the use of crops and strains unburdened by hereditary diseases and having high resistance to damaging effects;

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convenience and reliability of decomposition of the part of the biomass unsuitable as food.

We used all the principles formulated in the selection of a promising green conveyor carbohydrate root crop.

Plants of 18-20 botanical families are cultivated in the temperate zone and, in the tropics, of 69. The basic source of

starch in the temperate zone is only one species, the potato. About 100-150 species of starch bearing plants from 13 families are used to various degrees in the tropics.⁶ For comparison, we selected 15 species of starch bearing root and tuber plants, which were divided into 3 groups, according to the worldwide distribution.

Group A includes crops which occupy considerable areas and are the main source of nutrition for the majority of the peoples of the earth. Of them, the potato is in first place in the world by popularity and area occupied. It is cultivated everywhere, from the Arctic Circle to mountain areas in the tropics. However, the primary geographic range is the temperate zone, where potato harvest and quality are especially high. The potato is a productive crop, with a relatively short growing period. Therefore, we selected it as the standard for evaluation of the other starch bearing crops. At the same time, the potato is considerably inferior to other crops of this group, in yield of dry matter per unit area. The presence of solanine, rest periods, propagation of the agriculturally useful biomass (roots), the inedibility of the plant tops and low resistance to diseases are all unfavorable qualities, which reduce the good qualities of the potato as a component of the higher plant link in closed life support systems.

The sweet potato is in second place by area occupied and popularity. The southern limit of potato cultivation approximately coincides with the northern limit of mass occurrence of the sweet potato, which is no less popular in the tropical and subtropical zones than the potato in the temperate. In many countries of Africa, Asia and Latin America, the sweet potato is the basic source of human carbohydrate nutrition. Due to the sweetish taste, similar to that of squash, the sweet potato is called the "sweet potato" in America. A less sweet variety of the sweet potato

⁶Sinyagin, I.I., Tropicheskoye Zemledeliye [Tropical Agriculture], Moscow, 1969; Vul'f, K.V. and O.F. Maleyeva, Mirovyye resursy poleznykh rasteniy [World Resources of Useful Plants], Leningrad, 1969.

is similar to the taste of boiled chestnuts and others, not sweet, do not differ from the potato in taste. The root harvest from one plant is from 0.5 to 1.0 kg or more, on the average (in separate cases, up to 16-25 kg from a bush). The entire sweet potato biomass is edible. The dry matter content of the root is richer than many of the tuber and root crop group. It approaches the cereals in this property. The maximum amount of dry matter sometimes reaches 45%. Sweet potato leaves and young stalks are rich in vitamins and mineral salts, they have up to 5-6% protein content they have a pleasant, slightly acid taste, and they are used to make salads. The dried leaves preserve their chemical composition. All species of animals willingly eat the fresh and dried sweet potato tops. Cuttings are used as planting material. Therefore, the entire root crop can go for food. The food preparation technology is simple and diverse. It is consumed in the baked, boiled, fried and preserved forms. All recipes for preparing potato dishes are suitable for the sweet potato. The optimum growing temperature for the sweet potato is somewhat higher than for the potato; approximation 24-30°. However, the sweet potato withstands greater variations in temperature, from 12 to 45°.

The other species of group A (manioc, chinese yam, colocasia)^{*} also are used by the population of tropical regions as food and industrial crops. These are production crops with a high dry matter content in the roots but, because of the extremely long growing period (300-400 days), the output per unit time of these crops decreases sharply. These are distinctly tropical species. They occupy similar geographic ranges. Manioc is grown more in South America, sweet potatoes in Southeast Asia and Indonesia, and colocasia, in these and other areas.

All the species of group A except sweet potatoes contain various toxic and irritating substances (potato, solanin; manioc, hydrocyanic acid; colocasia, saponins, sometimes hydrocyanic acid), removed by culinary and other methods of treatment.

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Group B is made up of less widespread crop species, with a longer growing period, on the order of a year or more. They all are less productive than the potato and are inferior to it in output. Maranta, canna and arracacia are grown most of all, to obtain the high quality technical arrowroot starch. The young plants usually are used for food, since the mature roots become highly fibrous and are little suited for food. Xanthosoma, amorphophallus and cyrtosperma (all of the Araceae family) occupy the same geographic range. These moisture loving plants reach a height of 2-3 m. There are nodules of calcium oxalate in all elements of the plants.

Group C includes narrowly local species with relatively small geographic ranges. They usually are grown in farm plots, as garden crops. There is little data in the literature on three species, and their chemical composition has not been described. Despite the antiquity of cultivation of the species (oxalis tuberosa, ullucus tuberosus, tropaeolum tuberosum) in the mountainous regions of Chile, Peru, Ecuador and Bolivia, as well as their broad popularity among the local population, they are almost undescribed in the literature. The geographic range of these species is connected with their basic biological properties; they are typical short day plants. Coleus is a crop of tropical Africa and Madagascar. The compactness of the bush and the similar chemical composition of the roots to the potato attract attention but little previous study of them does not permit sufficiently complete characterization of this crop.

On the basis of a comparative analysis of the roots of the carbohydrate plants, it can be concluded that sweet potato cultivation meets the necessary requirements most of all. Domestic and foreign authors have repeatedly considered the sweet potato as one prospective crop for development of a green conveyor in closed life support systems. Thus, as early as 1966, a group of

scientists from the USA Battelle Memorial Institute conducted tests of a hundred species of crop plants, to select the most promising for a space plantation. The sweet potato received the highest evaluation for "space life."⁷

Man has been acquainted with the sweet potato as a food crop for a very long time. The ancient Peruvians exported the sweet potato to the Pacific Ocean Islands in prehistoric times. There are many legends connected with the sweet potato on Easter Island, the Hawaiian Islands and in New Zealand.

Columbus first imported the sweet potato to Europe. In 1566, it was described by the botanist Cluzis. From the Philippine Islands at the end of the 16th century, the sweet potato entered China, where it spread widely and quickly. Cultivation of the sweet potato closer than 25 kilometers from the city limits was forbidden in Peking in 1839, since many years of sweet potato planting had formed dense thickets.

In Russia, in 1828, N. Shcheglov first wrote of the sweet potato, as a crop which "multiplies powerfully on the Black Sea coast." As early as 1896, near Sukhumi, a sweet potato output of 1500 poods per tenth part (240 centners per hectare) was obtained. A large part in the spread of the sweet potato in Russia belongs to Dr. F. Kryshtofovich, the Russian agricultural agent in North America in the 1900-1912 period. He repeatedly sent sweet potato roots and persistently popularized it in the newspapers and journals. He wrote: "We will not forget that the introduction of each new plant is connected with great difficulties, to a certain extent. The potato was introduced into Russian by the force of arms, and this caused numerous riots... the sweet potato must not be disregarded, only because of its tropical origin, since the potato, and tomato, and corn, and many other of the

⁷Neth. J. Agric. Sci. 15, 241-248 (1967).

garden plants are of tropical origin, which does not interfere with us in growing them everywhere in Russia."⁸

In 1927, on the initiative of N.I. Vavilov, several varieties of sweet potato from the USA and China were supplied to the Sukhimi test station. Breeding and study of the sweet potato crop by Soviet scientists began at this time but, unfortunately, it has remained a collective crop up to now.⁹

Thus, we brought our selection to a stop on the sweet potato, as the principal claimant to the position of basic crop of the higher plant link, and we proceeded to experimental testing of the conclusions.

The first series of tests was conducted in Yerevan, at the base of the Institute of Agrochemical Problems and Hydroponics, Academy of Sciences Armenian SSR, headed by one of the leading specialists in the field of hydroponic plant growing, Academician /115 G.S. Davtyan. For a period of two years in the field and in open hydroponics, ten varieties of sweet potato were grown. These varieties were selected from the collection of the Sukhimi test station, All-Union Institute of Plant Growing (about 60 varieties), on the basis of the criteria developed.

Good root crop yields were obtained. The majority of plants in the field and in the hydroponic farm yielded more than 1 kg, and individual plants in the hydroponic farm yielded more than 5 kg. The dry matter content of the root crops was from 20 to 30%, including 15-25% starch and 1-6% sugar. The plants of some varieties had thick, well developed tops, the weight of which

⁸Mattson, H.J., International Science and Technology, Vol. 54, p. 28-37.

⁹Kryshofovich, F., Sel'skiy khozyain 14, 415(1900); 18-19, 489 (1912).



Root crop of sweet potato grown in the field (on the left) and hydroponically.

from one plant reached up to 2 kg. The weight of the tops at harvest of plants of other varieties was 100-300 g. The dry matter content of the sweet potato leaves varied from 15 to 18%. The amount of vitamin C was from 15 to 150 mg%, and it varied, depending on weather conditions. The carotene content was from 40 to 60 mg%.¹⁰ The young leaves proved to be completely suitable for salads, and they were similar to spinach in taste.

The second series of tests was conducted with the same varieties under laboratory conditions. Incandescent lamps and xenon lamps were used for illumination. The most promising variety (Hua-bey 350) was selected as a result of the experiments. We grew this variety in a special chamber, with conditions close to optimum for the sweet potato.¹¹

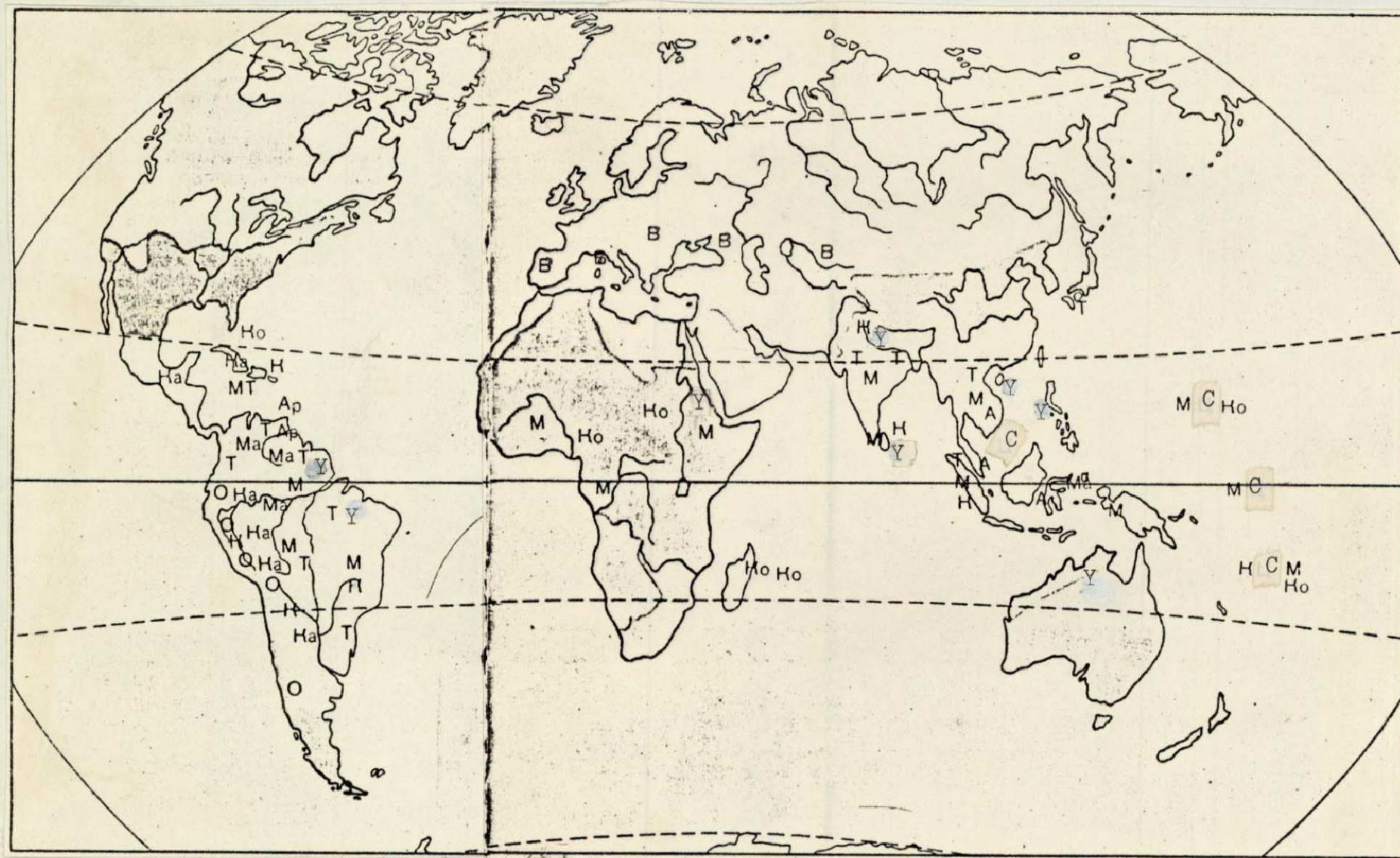
After 150 days, the total weight of the sweet potato biomass was 17.8 kg/m², and the harvested root crop weighed 5.8 kg/m² (with 23.4% dry matter). The sweet potato harvest weighed approximately 4.5 kg in dry form, which gave 30 g of dry matter from 1 m² per day. These figures are close to those required of plant productivity for closed life support systems.

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The sweet potato cultivation experiments are representative

¹⁰Tyutin, M.G., Selektsiya batata [Sweet Potato Breeding], Leningrad, 1937.

¹¹Nikishanova, T.I., "The sweet potato and the possibilities of its hydroponic cultivation in Armenia," Soobshcheniya Instituta agrokhimicheskikh problem i gidroponika (Yerevan) 12, (1972).



Map of world distribution of root crops.

☐	Potato, Ka, potato in mountain regions	☐ M	Manioc	☐ C	Cyrrhosperma	☐ O	oxalis tuberosa, ullucus tuberosa, tropaeolum tuberosum
☐ B	Sweet potato	☐ Y	Yam	☐ Ap	Araceae		
☐	Sweet potato, colocasia, Manioc	☐ A	Amorphophallus	☐ Ma	Maranta		
☐ T	Taro, colocasia	☐ H	Canna	☐ Ho	Coleus		

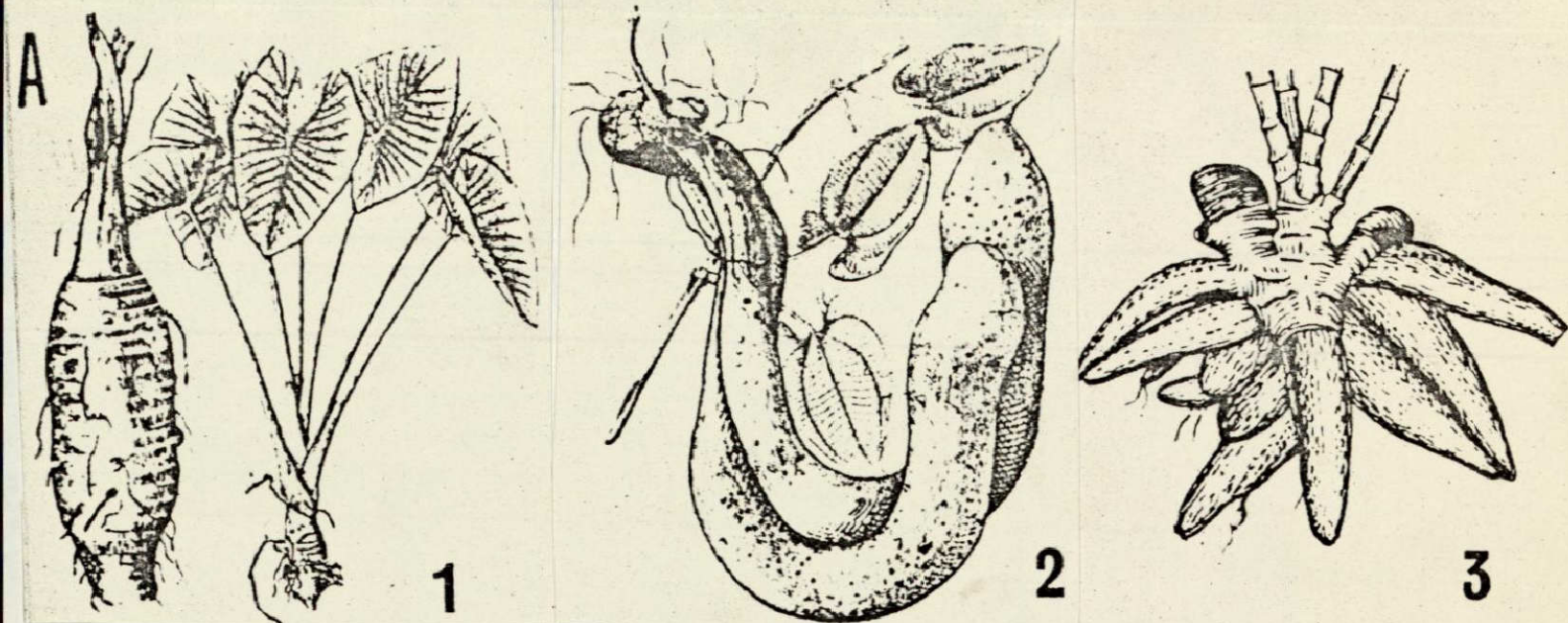


Fig. A. Starch bearing species of group A: 1. colocasia, 2. yam, 3. manioc root.

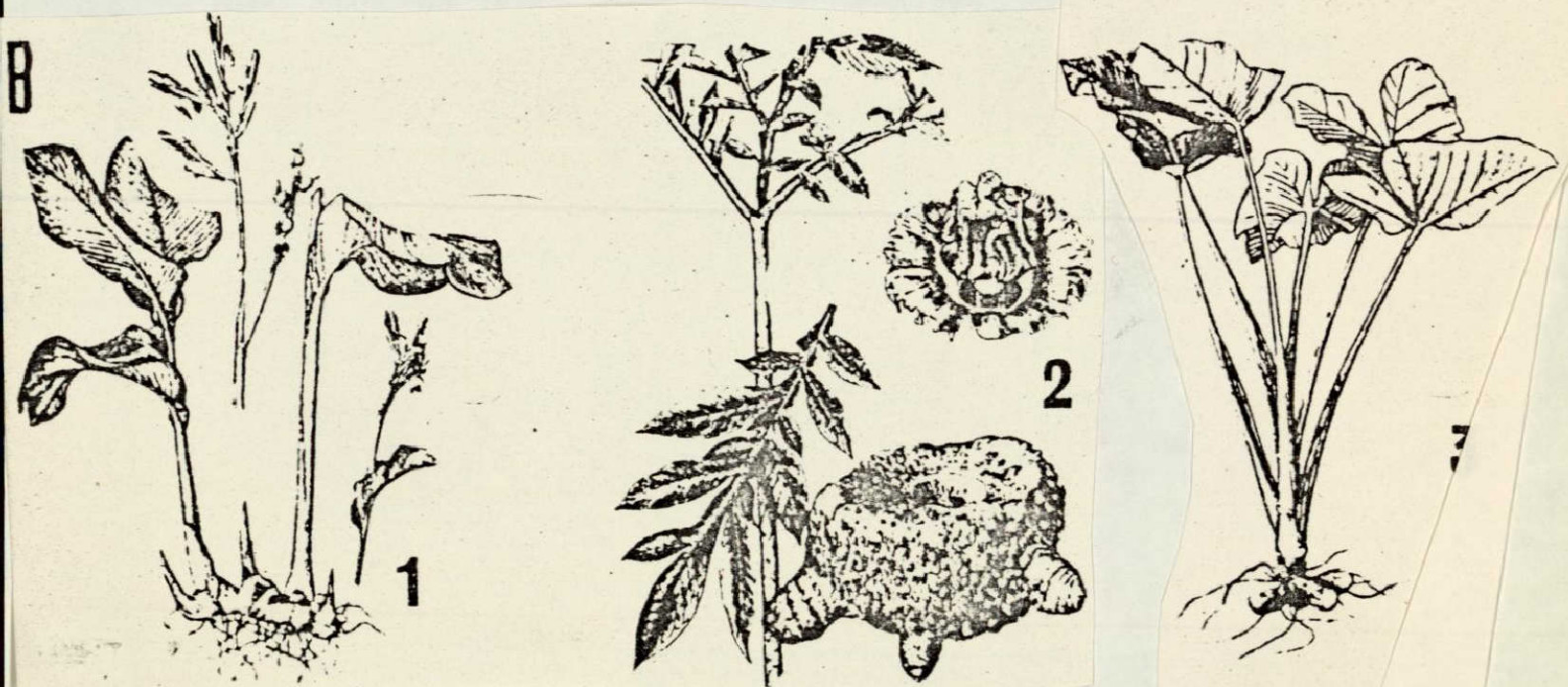


Fig. B. Starch bearing species of group B: 1. edible canna, 2. amorphophallus, 3. xanthosoma.

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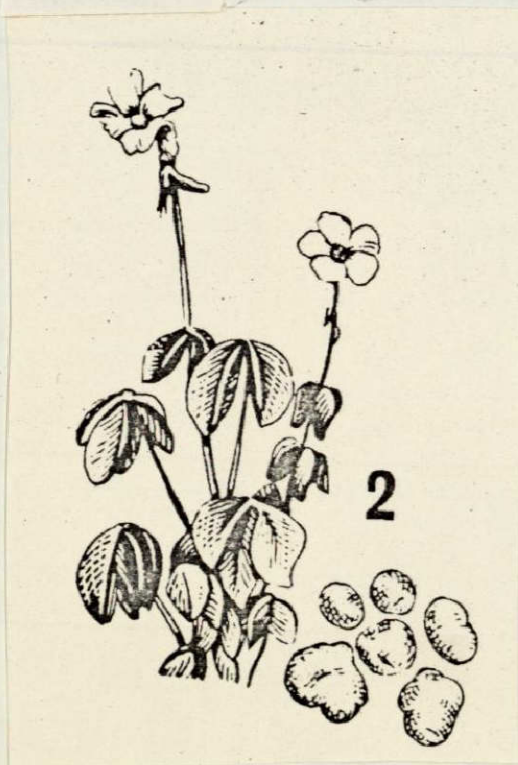
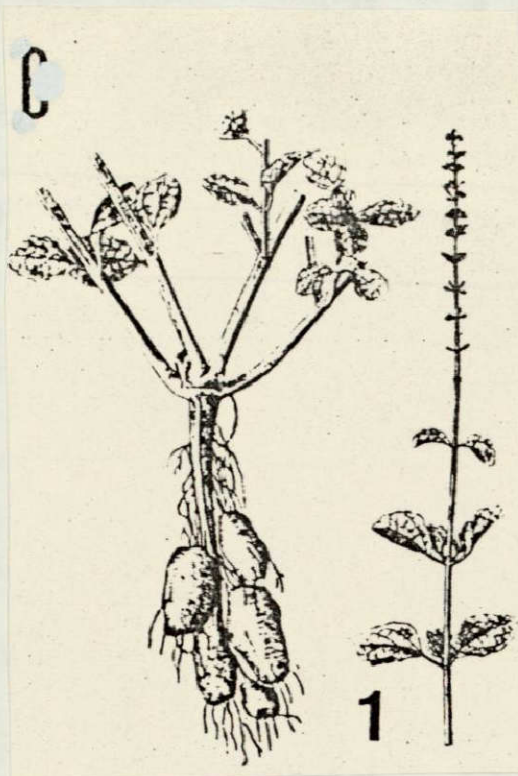


Fig. C. Starch bearing species of group C: 1. coleus, 2. oxalis tuberosa.

(approximate), and they require continuation, with sequential approximation of conditions of their development towards the environmental conditions of air tight, manned space vehicle cabins, covering the maximum possible number of sweet potato varieties. However, the first results permit it to be concluded that sweet potato cultivation is suitable for a closed life support system, and that the set of criteria /117 developed can be used for preliminary evaluation of crops as possible candidates for use in these systems.

Thus far, the sweet potato is not widespread in our country. However, the high food value of its root crop and the edible top permit more widespread use of this crop in agricultural practice to be recommended. The organization of special sweet potato variety breeding is desirable, both to advance it to more northern regions of the country, and for covered soil and closed life support systems.



General view of sweet potato with root crops.
Figure, A.P. Bykova

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ECONOMIC AND BIOLOGICAL CHARACTERISTICS OF STARCH FORMING ROOT CROP SPECIES GROWN ON THE EARTH

Name	Botanical Family	World Distribution	Size and Description of Plant	Growing Period Days	Average Yield, centner per hectare	Content, %			Toxic Substances	Reproduction Method	No. of plants per hectare times 10 ³
						Dry Matter	Starch	Sugar			
GROUP A -- Widespread species											
Potato (Solanum tuberosum L.)	Solanaceae	Everywhere temperate zone, tropics, mountain regions	50-60 cm herbaceous bush	90-150	200-300 (45-100 in tropics)	15-25	10-20	1-2	Solanine	Tubers	40
Sweet potato (Ipomoea batatas Poir.)	Convolvulaceae	Everywhere tropics, subtropics, warm temperate zones	Creeping, 0.5-6 m	90-180	200-300	25-40	20-35	2-6	None	Cutting, shoots	30-40
Manioc, cassava (Manihot utilissima Pohl)	Euphorbiaceae	Tropical Africa, Southeast Asia, South America	2-5 m woody bush	300-500	70-200	30-45	20-30	2-3	Cyanide compounds	Parts of stem, cuttings	80-10
Colocasia, taro (Colocasia esculenta L.)	Araceae	Tropical Africa, Southeast Asia, Oceania	100-120 cm herbaceous bush	90-240	100-400	20-30	15-25	1-2	Calcium oxalate nodules irritating mucosa	Small tubers, shoots	20-30
Yam (Dioscorea sp.)	Dioscoreaceae	Tropical Southeast Asia, Southwest Africa	Creeping up to 6 m	Undetermined	200-300	25-30	20-25	3-5	Some species poisonous	Cuttings, parts of tubers	10-15
Group B -- Less widespread species											
Maranta (Maranta arundinacea L.)	Marantaceae	Tropical West Indies, Australia, Northern Brazil	Herbaceous bush up to 1 m	360 or more	300-360	25-40	20-35	1-2	None	Same	20-25
Canna (Canna edulis Ker - Gawl.)	Cannaceae	South America, less in Asia	Herbaceous bush up to 2 m	180-270	250-270	30	20-28	1-2	None	"	10-15
Arracacia (Arracacia xanthorrhiza Bancr.)	Umbelliferae	Panama, West Indies	0.6-1 m herbaceous bush	300-360	400-500	20-25	15-17	1-2	None	"	25-30

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TABLE CONTINUED

Name	Botanical Family	World Distribution	Size and Description of Plant	Growing Period Days	Average Yield, centner per hectare	Content, %			Substances	Reproduction Method	No. of plants per hectare times 10 ³
						Dry Matter	Starch	Sugar			
Xanthosoma (Xanthosoma sagittifolium Schott.)	Araceae	Tropical West Indies, America	Herbaceous bush up to 2 m	240-360	100-200	25-30	20-25	1-2	None	Same	20-30
Amorphophallus (Amorphophallus spp.)	Araceae	Indonesia, Oceania	Up to 2 m	300-500	100-200	25-30	20-25	1-2	None	"	10-15
Cyrtosperma (Cyrtosperma tuberosa L.)	Araceae	Indonesia, Oceania	3-3.5 m	300-500	100-150	37	34	1-2	None	"	10-15
Group C -- Narrowly local species											
Coleus (Coleus tuberosus L.)	Labiatae	Tropical Africa, Madagascar	0.6-0.7 m herbaceous bush	150-180	150-200	28	23	1-2	None	Tubers	40-50
Oxalis (Oxalis tuberosa Molina)	Oxalidaceae	Andes-Peruvian region	" "	270	-	-	-	-	Calcium oxide crystals	"	40-50
Ullucus (Ullucus tuberosus Lozano)	Basellaceae	South America, Andes,	" "	270	-	-	-	-	None	"	40-50
Tropaeolum (Tropaeolum tuberosum R. et. P.)	Tropaeolaceae	In mountain regions of Venezuela, Bolivia, Peru	" "	270	-	-	-	-	None	"	40-50

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