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Introduction

Food, water, and a breathable atmosphere are three elements fundamental to human survival. Expendable supplies of these elements may be carried onboard spacecraft for brief spaceflights; for permanent missions in low Earth orbit, they may be resupplied from Earth, though only at high cost. Missions to more distant places, such as the moon, Mars and beyond, however, will require regeneration of food, air, and water. An autonomous bioregenerative life support system that continually recycles the solid, liquid, and gaseous materials essential for human life is the goal of NASA’s Controlled Ecological Life Support System (CELSS) Program.

NASA has conducted research in various aspects of closed regenerative life support systems since the 1960s. In 1979, the CELSS Program was established in the Life Sciences Division, located within NASA’s Office of Space Science and Applications, to encompass Life Sciences’ CELSS efforts in one program. CELSS research and technology development is currently being performed in a broad range of areas, including food production, nutritional requirements, waste management, and systems management and control.

**Food Production.** This subject area includes determining the optimal plant species (both higher and lower plants) that will provide a large percentage of edible plant biomass, maximum yield, and maximum nutrient value, while using a minimum of space and power. Another aspect of Food Production includes controlling the system’s environment, i.e., examining and regulating such factors as temperature, airflow, humidity, CO₂ level, and illumination to provide for optimal growth and production. Researchers also explore methods to convert inedible biomass to food.

**Nutritional Requirements.** This area involves analyzing human nutritional requirements on Earth and in microgravity and determining which crop species under consideration for a CELSS will meet these requirements.

**Waste Management.** Research in this subject area examines the control of CO₂, O₂, and trace gas contaminants; atmospheric regeneration; water purification for spent nutrients and condensate; and recycling the constituents of solid and liquid human waste and nonedible biomass.

**Systems Management and Control.** This area examines the integration, monitoring, control, and stability of whole CELSS systems. This includes modeling and design of systems within sealed chambers that provide for atmospheric regeneration, food production and processing, and waste management, thus testing the research results obtained in the other research areas.

The purpose of compiling this bibliography is to provide the scientific community with a list of publications resulting from CELSS-related research, from its official beginnings in 1979 through mid-1989. Certain papers published prior to 1979 that involve background research leading to the development of the CELSS Program are also included. It is anticipated that the bibliography will stimulate the exchange of information and ideas between scientists working in different areas of the program and in the field of bioregenerative life support in general.
The arrangement of citations in this bibliography follows the four divisions of research outlined above. Publications are listed alphabetically by author within the research area with which they are most closely associated. Authors conducting research under the auspices of the CELSS Program have been identified with an asterisk.

The assistance of the CELSS Principal Investigators in providing lists of their publications and the technical assistance of Rodney P. Johnson are gratefully acknowledged.

Maurice M. Averner, Ph.D.
NASA CELSS Program Manager
FOOD PRODUCTION: Higher Plants
Akers, C.P.; Akers, S.W.; Mitchell*, C.A.
The Minitron System for growth of small plants under controlled environment conditions.

Akhavan-Kharazian, M.; Campbell, W.F.; Bugbee, B. (Salisbury, F.B. = P.I.)
Calcium amelioration of NaCl effects on leaf expansion, photosynthesis, and transpiration in *Phaseolus vulgaris* L. (Abstract).

Aslam, M.; Harbit, K.B.; Huffaker*, R.C.
Comparative effect of selenite and selenate on nitrate assimilation in barley seedlings (Abstract).
*Plant Physiology* 86(4, Suppl.): 58, 1988. (GWU 11155)

Aslam, M.; Huffaker*, R.
Effects of various forms of nitrogen nutrition on the development of nitrate and nitrite reductase activities in *Glycine max* (L.) Merr (Abstract).
*Plant Physiology* 75(1, Suppl.): 119, 1984. (GWU 5756)

Aslam, M.; Huffaker*, R.
*In vivo* nitrate reduction in roots and shoots of barley *Hordeum vulgare* L. seedlings in light and darkness.

Aslam, M.; Huffaker*, R.C.
Effects of sugars on *in vivo* nitrate reduction in barley leaves in light and darkness under aerobic conditions (Abstract).
*Plant Physiology* 72(1, Suppl.): 129, 1983. (GWU 4487)

Aslam, M.; Huffaker*, R.C.
Role of nitrate and nitrite in the induction of nitrite reductase in leaves of barley seedlings.
*Plant Physiology* 91: 1152-1156, 1989. (GWU 10971)

Aslam, M.; Huffaker*, R.C.
Role of nitrate and nitrite in the induction of nitrite reductase in barley leaves (Abstract).

Aslam, M.; Huffaker*, R.C.
Role of nitrite in the induction of nitrate reductase activity in barley leaves (Abstract).
*Plant Physiology* 80(4, Suppl.): 41, 1986. (GWU 8827)

Aslam, M.; Rosichan, J.L.; Huffaker*, R.C.
Comparative induction of nitrate reductase by nitrate and nitrite in barley leaves.

Aslam, M.; Rosichan, J.L.; Huffaker*, R.C.
Induction of nitrate and nitrite reductase activities by NO$_3^-$ and NO$_2^-$ in barley leaves (Abstract).
*Plant Physiology* 77(4, Suppl.): 45, 1985. (GWU 10242)

Early effects of salinity on nitrate and ammonium assimilation in barley seedlings (Abstract).
*Plant Physiology* 75(1, Suppl.): 65, 1984. (GWU 5827)
Barta, D.J.; Tibbitts*, T.W.  
Characteristics of high intensity discharge lamps (Abstract).  
*HortScience* 17(3): 493, 1982. (GWU 6270)

Barta, D.J.; Tibbitts*, T.W.  
Diurnal fluctuations in calcium and magnesium concentration of lettuce leaves (Abstract).  

Barta, D.J.; Tibbitts*, T.W.  
Effects of artificial enclosure of young lettuce leaves on tipburn incidence and leaf calcium concentration.  

Barta, D.J.; Tibbitts*, T.W.  

Barta, D.J.; Tibbitts*, T.W.  
Enclosure of young lettuce leaves: Effects of tipburn incidence and leaf calcium and magnesium concentration (Abstract).  
*HortScience* 19(3): 582-583, 1984. (GWU 6268)

Barta, D.J.; Tibbitts*, T.W.  
Mineral localization in young enlarging leaves of lettuce: Implications for tipburn development (Abstract).  
*HortScience* 21(3): 728, 1986. (GWU 11149)

Barta, D.J.; Tibbitts*, T.W.  
Use of electron microprobe x-ray analysis for determination of low calcium concentrations across leaf tissue (Abstract).  
*HortScience* 20(3): 555, 1985. (GWU 11160)

Barta, D.J.; Tibbitts*, T.W.  
Use of the wavelength-dispersive microprobe for determination of low calcium levels in plant tissues.  

Bennett, S.M.; Corey, B.R.; Bula, R.J.; Tibbitts*, T.W.  
Potential use of ion exchange materials in controlling nutrient balance of a recirculating solution for use in a CELSS (Abstract).  
*ASGSB Bulletin* 2: 38, 1989. (GWU 10427)

Bennett, S.M.; Tibbitts*, T.W.; Wheeler, R.M.; Fitzpatrick, A.H.  
Effect of diurnal temperature fluctuations on growth of potato (Abstract).  

Berry, W.; Hoshizaki*, T.; Ulrich, A.  
The effect of ultradian and orbital cycles on plant growth.  

Berry, W.L.; Koontz, H.V.; Wheeler, R.M.; Prince, R.P. (Knott, W.M. = P.I.)  
Criteria for evaluating experiments on crop production in space.  
Berry, W.L.; Krizek, D.T.; Ormrod, D.P.; McFarlane, J.C.; Langhans, R.W.; Tibbitts*, T.W.
Variation in elemental content of lettuce grown under base-line conditions in five controlled-environment facilities.

Tibbitts*, T.W.
Uniformity studies with lettuce in controlled environment chambers: Results of growth and tissue analysis.

Brooks, C.A.; Mitchell*, C.A.
Effect of salicylhydroxamic acid on endosperm strength and embryo growth of *Lactuca sativa* L. cv.
‘Waldmann’s Green’ seeds.

Brooks, C.A.; Mitchell*, C.A.
Sham stimulated dark germination of Waldmann’s Green lettuce (Abstract).
*Plant Physiology* 75(1, Suppl.): 69, 1984. (GWU 5830)

Brooks, C.A.; Yu, K.S.; Mitchell*, C.A.
Salicylhydroxamic acid potentiates germination of ‘Waldmann’s Green’ lettuce seed.

Bubenheim*, D.L.
The Crop Growth Research Chamber: A ground-based facility for CELSS research.

Bubenheim*, D.L.
The Crop Growth Research Chamber: A ground based facility for CELSS research (Abstract).
(GWU 10390)

Bubenheim, D.L.; Bugbee, B.; Salisbury*, F.B.
Effect of water filters on radiation in controlled environments (Abstract).

Bubenheim, D.L.; Bugbee, B.; Salisbury*, F.B.
Growth and yield of wheat in photoperiods characteristic of polar and equatorial earth orbits (Abstract).

Bubenheim, D.L.; Bugbee, B.; Salisbury*, F.B.
Influence of a roof applied water layer on radiation, cooling requirements, and CO₂ enrichment efficiency in a greenhouse (Abstract).

Bubenheim*, D.L.; Bugbee*, B.; Salisbury*, F.B.
Low-irradiance blue-light induced lignin synthesis in wheat (Abstract).
*Plant Physiology* 89(4, Suppl.): 22, 1989. (GWU 11013)

Bubenheim*, D.L.; Bugbee, B.; Salisbury*, F.B.
Radiation in controlled environments: Influence of lamp type and filter material.
Bubenheim, D.L.; Dreschel, T.W.; Mitchell*, C.A.  
Comparison of plant growth in a tubular membrane hydroponic system with that in conventional hydroponic culture (Abstract).  

Bubenheim, D.L.; Mitchell*, C.A.  
Cowpea harvest strategies and yield efficiency for space food production (Abstract).  

Bubenheim, D.L.; Mitchell*, C.A.  
Evaluation of new candidate crop species for CELSS (Abstract).  

Bubenheim, D.L.; Salisbury*, F.B.  
Photoperiod sensitivity of wheat (Abstract).  
*Plant Physiology* 77(4, Suppl.): 110, 1985. (GWU 8510)

Bugbee*, B.  
Carbon use efficiency in optimal environments.  

Bugbee, B. (Salisbury, F.B. = P.I.)  
Design and maintenance of recirculating hydroponic systems (Abstract).  

Bugbee*, B.  
Exploring the limits of crop productivity: A model to evaluate progress (Abstract).  

Bugbee, B. (Salisbury, F.B. = P.I.)  

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When does CO₂ enrichment become toxic to plants? (Abstract)  

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Temperature/photoperiod effects on reproductive development in a long-day plant (wheat) (Abstract).  
*Plant Physiology* 80(4, Suppl.): 3, 1986. (GWU 8767)

Bugbee, B.; Guerra, D.; Salisbury*, F.  
A simple, effective modification for increasing radiation in controlled environments (Abstract).  

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Evaluation of pH buffering agents for nutrient solution studies (Abstract).  
*Plant Physiology* 72(1, Suppl.): 5, 1983. (GWU 4473)
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Exploring the limits of crop productivity: Photosynthetic and carbon partitioning efficiency in an optimizing environment (Abstract).

Bugbee, B.; Salisbury*, F.B.
Food production in simulated microgravity (Abstract).

Bugbee, B.; Salisbury*, F.B.
Iron nutrition of wheat in solution culture (Abstract).
*HortScience* 17(3): 514, 1982. (GWU 4761)

Bugbee, B.; Salisbury*, F.B.
Physiological and genetic studies on wheat for the controlled environments of space (Abstract).

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The role of phasic environmental control in lunar food production efficiency: Architectural implications (Abstract).
In: *Symposium on Lunar Bases and Space Activities in the 21st Century*, Houston, TX, April 5-7, 1988, p. 38. (GWU 10501)

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Wheat production in the controlled environments of space.

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Tomato growth as affected by root-zone temperature and the addition of giberellic acid and kinetin to nutrient solutions.

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Controlled environment crop production: Hydroponic vs. lunar regolith.

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*ASGSB Bulletin* 1: 30-31, 1988. (GWU 8837)

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Exploring the limits of crop productivity. I. Photosynthetic efficiency of wheat in high irradiance environments. 

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Studies on maximum yield of wheat for the controlled environments of space. 

Bula, R.J.; Corey, R.B.; Volkweiss, S.J.; Tibbitts*, T.W. 
Concepts for a commercial space-based plant growth unit (Abstract). 

Bula, R.J.; Morrow, R.C.; Tibbitts*, T.W. 
Technology for subsystems of space-based plant growth facilities (Abstract). 

Campbell*, W.F. 
Interactive effects of temperature and humidity on onion pollen germination and pollen tube growth (Abstract). 
*HortScience* 17(1): 26, 1982. (GWU 5210)

Campbell*, W.F.; Wagenet, R.J.; Rodriguez, R.R. 
Fertility, salinity and water management interactions on yield components and nitrogen fixation in *Phaseolus* L. (Abstract). 
*HortScience* 17(3): 479, 1982. (GWU 4762)

Optimizing nutrient, phytohormone and gas concentrations for mass propagation of wheat through somatic embryogenesis (Abstract). 

Carman, J.G.; Hess, J.R.; Bugbee*, B. 
Cloning plant embryos by simulating ovular conditions in controlled environments (Abstract). 
*ASGSB Bulletin* 3(1): 63, 1989. (GWU 11041)

Glycoalkaloids of potato tubers grown under controlled environments (Abstract). 

Coe, L.L.; Mitchell*, C.A. 
Ability of chemical growth promoters to negate mechanical stress effects on dark grown pea seedlings (Abstract). 
*ASGSB Bulletin* 3(1): 63, 1989. (GWU 11040)
Coe, L.L.; Mitchell*, C.A.
*Plant Physiology* 89(4, Suppl.): 104, 1989. (GWU 11011)

Collier, G.F.; Tibbits*, T.W.
Effects of relative humidity and root temperature on calcium concentration and tipburn development in lettuce.

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*Horticultural Reviews* 4: 49-65, 1982. (GWU 6269)

Effects of NaCl on metabolic heat evolution rates by barley roots.

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Nitrogen uptake by wheat seedlings, interactive effects of four nitrogen sources: NO₃⁻, NO₂⁻, NH₄⁺, and urea.

Cuellar, M.D.; Mitchell*, C.A.
Effects of static vs. flowing atmospheres on plant growth in the space shuttle plant growth unit (Abstract).

Cure, J.D.; Raper*, C.D., Jr.; Patterson, R.P.; Robarge, W.P.
Dinitrogen fixation in soybean in response to leaf water stress and seed growth rate.
*Crop Science* 25: 52-58, 1985. (GWU 11150)

Davis, T.L.; Nielson, S.S.; Mitchell*, C.A.
Interactive effects of CO₂ enrichment, radiation enhancement, and nitrogen form and level on growth and nutritional value of leaf lettuce (Abstract).

Dreschel, T.W. (Knott, W.M. = P.I.)
The Results of Porous Tube Plant Growth Unit Experiment T6B. Kennedy Space Center, FL: NASA, Kennedy Space Center, 1988. (NASA-TM-100988)

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Status of porous tube plant growth unit research: Development of a plant nutrient delivery system for space.

Development of a membrane nutrient system (Abstract).
Porous membrane utilization in plant nutrient delivery.

Tubular membrane plant growth unit for hydroponics in microgravity.
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Control of water and nutrients using a porous tube: A method for growing plants in space.

Plant growth in a porous tube nutrient delivery system: The effects of pressure and pore size on productivity (Abstract).

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Factors affecting plant growth in membrane nutrient delivery (Abstract).

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Nodule activity and allocation of photosynthate of soybean during recovery from water stress.

Ford, T.L.; Mitchell*, C.A.
Effects of HPS with low level MH + QI illumination on growth and chlorosis of leaf lettuce in growth chambers (Abstract).

Gale, J.; Smernoff, D.; Macler, B.; MacElroy*, R.D.
Carbon balance and productivity of Lemna gibba, a candidate plant for CELSS (Abstract).
In: Proceedings of the 27th Plenary Meeting of the Committee on Space Research, Espoo, Finland, July 18-29, 1988, p. 391. (GWU 10429)

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Major gene control of nitrate-reductase activity in common wheat.
Crop Science 20: 717-721, 1980. (GWU 3098)

Garland, J.L.; Garland, R.F. (Knott, W.M. = P.I.)
Bacterial rhizosphere interactions in hydroponically grown wheat (Abstract).

Garland, J.L.; MacKowiak, C.L.; Strayer, R.F. (Knott, W.M. = P.I.)
Utilization of the soluble fraction of cold water leachate from inedible wheat biomass in a controlled ecological life support system (Abstract).
ASGSB Bulletin 2: 37, 1989. (GWU 10423)
Garland, J.L.; Strayer, R.F. (Knott, W.M. = P.I.)
Bacterial dynamics in wheat hydroponic culture subsystems of CELSS (Abstract).

Garland, J.L.; Strayer, R.F. (Knott, W.M. = P.I.)

Goeschl, J.D.; Sauer, R.L.; Scheld*, H.W.
A method for screening of plant species for space use.

Goknur, A.B.; Tibbitts*, T.W.
Dark opening of stomata as related to SO₂ sensitivity of potatoes (Abstract).

Goyal, S.S.; Huffaker*, R.C.
Induction and kinetics of NO₃⁻, NO₂⁻ and NH₄⁺ uptake systems in wheat (*Triticum aestivum* L.) (Abstract).
*Plant Physiology* 75(1, Suppl.): 11, 1984. (GWU 5823)

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Induction of NO₃⁻ transport system in wheat seedlings: Effect of NH₄⁺ and NO₂⁻ (Abstract).

Goyal, S.S.; Huffaker*, R.C.
Interactions among nitrate, nitrite and ammonium during assimilation in detached barley leaves (Abstract).
*Plant Physiology* 65(6, Suppl.): 16, 1980. (GWU 3897)

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*Plant Physiology* 72(1, Suppl.): 110, 1983. (GWU 4490)

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A novel approach and a fully automated microcomputer-based system to study kinetics of NO₃⁻, NO₂⁻ and NH₄⁺ transport simultaneously by intact wheat seedlings.

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*Plant Physiology* 82: 1051-1056, 1986. (GWU 11017)
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Determination of ammonium ion by fluorometry or spectrophotometry after on-line derivatization with \( \alpha \)-phthalaldehyde.
*Analytical Chemistry* 60: 175-179, 1988. (GWU 11175)

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Proliferation of maize (*Zea mays* L.) roots in response to localized supply of nitrate.

Granato, T.C.; Raper*, C.D., Jr.; Wilkerson, G.G.
Respiration rate in maize roots is related to concentration of reduced nitrogen and proliferation of lateral roots.
*Physiologia Plantarum* 76: 419-424, 1989. (GWU 11134)

Guerra, D.; Anderson, A.J.; Salisbury*, F.B.
Reduced phenylalanine ammonia-lyase and tyrosine ammonia-lyase activities and lignin synthesis in wheat grown under low pressure sodium lamps.

Guerra, D.; Salisbury*, F.B.
Effects of long term exposure of wheat to diverse spectral environments: In vivo control mechanism of the phenylpropanoid pathway (Abstract).
*Plant Physiology* 72(1, Suppl.): 163, 1983. (GWU 4472)

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The effects of salt stress on nitrogen uptake and metabolism in barley (Abstract).
*Plant Physiology* 72(1, Suppl.): 135, 1983. (GWU 4492)

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Base-line growth studies of 'Grand Rapids' lettuce in controlled environments.

Heath-Pagliuso, S.; Huffaker*, R.C.; Allard, R.W.
Inheritance of nitrite reductase and regulation of nitrate reductase, nitrite reductase, and glutamine synthetase isozymes.

Henninger*, D.L.; Lagle, C.W.; Ming, D.W.
Lunar agricultural soils (Abstract).
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Lunar agricultural 'soils' (Abstract).

Henninger*, D.L.; Lagle, C.W.; Ming, D.W.
A lunar derived 'soil' for the growth of higher plants.

Henninger*, D.L.; Ming, D.W.; Lagle, C.W.
Extraterrestrial 'soils' for the growth of higher plants (Abstract).

Henry, L.T.; Raper*, C.D., Jr.
Cyclic variations in nitrogen uptake rate of soybean plants.
*Plant Physiology* 91: 1345-1350, 1989. (GWU 10972)

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Effects of root zone acidity on utilization of nitrate and ammonium in tobacco plants.

Hoenecke, M.E.; Bula, R.J.; Tibbits*, T.W.
Lettuce seedling response to red light-emitting diodes supplemented with varying levels of blue photons (Abstract).
*ASGSB Bulletin* 3(1): 59, 1989. (GWU 11038)

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*Physiologist* 27(6, Suppl.): S137-S138, 1984. (GWU 10245)

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Howe*, J.M.; Hoff*, J.E.
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Biochemistry and physiology of leaf proteins.

Huffaker*, R.C.

Selection of crop varieties for efficient production using urea, ammonia, nitrite, and nitrate in CELSS.

Huffaker*, R.C.; Aslam, M.; Ward, M.R.

Efficiency of N use by wheat as a function of influx and efflux of NO₃⁻ (Abstract).

Huffaker*, R.C.; Miller, B.L.

Reutilization of ribulose bisphosphate carboxylase.

Huffaker*, R.C.; Rains, D.W.; Qualset, C.O.


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*Developing a Basis for the Use of NO₃⁻, NO₂⁻, NH₄⁺ and Urea to Produce Wheat for CELSS.

Huffaker*, R.C.; Ward, M.R.

Effects of NO₃⁻, NH₄⁺, and urea on each other's uptake and incorporation.

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Effect of iodine disinfection products on higher plants.

Janik, D.S.; Macler, B.A.; MacElroy*, R.D.; Thorstenson, Y.R.; Sauer, R.L.

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Klobus, G.; Huffaker*, R.C.
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Characteristics of injury and recovery of net NO₃⁻ transport of barley seedlings from treatments of NaCl.

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Publications of research sponsored by the NASA CELSS (Controlled Ecological Life Support System) Program from 1979 to 1989 are listed. The CELSS Program encompasses research and technology with the goal of developing an autonomous bioregenerative life support system that continually recycles the solid, liquid, and gaseous materials essential for human life. The bibliography is divided into four major subject areas: food production, nutritional requirements, waste management, and systems management and control.

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