The IBIS (Italian Bioregenerative Systems) Working Group Advances the Life Support Sector

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Environmental Control & Life Support based on bio-regenerative technologies is a multidisciplinary theme, rapidly developing in the international arena and presenting a robust scientific and industrial background in Italy. The theme, crucial for space exploration, includes the development of closed-loop systems for the affordable human exploration and colonization of the Solar System. It is as well connected to the more traditional agriculture and civil / environmental areas, with a high potential for transferring knowledge and technologies developed for Space and with the expectation of a significant contribution to sustainability issues, via increased resource and energy use efficiency.

The theme of the Bio-regenerative Life Support is one of the key assets in the Horizon 2020 Agenda of the European Commission, in the Global Exploration Roadmap and in the European Space Agency and Italian Space Agency roadmaps.

In this framework, it was deemed appropriate to create a national network of stakeholders, a forum for the exchange of information and ideas, and to initiate and coordinate specific actions that could stimulate and encourage research, industrial and business initiatives on the subject.

The IBIS (Italian Bioregenerative Systems) Working Group has been established bringing together the scientific and industrial experts on the subject, also through the organization of specific national and international events; to encourage the exchange of ideas and information; and to contribute to the formation of a national vision for the medium and long term.

This paper describes the initiatives of the IBIS WG conducted to date and the most significant results, including the harmonization of Italian research activities and the scientific and outreach events organized by the WG, as well as the expected future activities.

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Nomenclature

ASI	=	Agenzia Spaziale Italiana (Italian Space Agency)
ATV	=	Automated Transfer Vehicle
BLSS	=	Bioregenerative Life Support Systems
CAB	=	Controllo Ambientale Biorigenerativo (Bioregenerative Environmental Control)
CFD	=	Computational Fluid Dynamics
ECLS	=	Environmental Control & Life Support
EC	=	European Commission
ESA	=	European Space Agency
ESM	=	Equivalent System Mass
FCU	=	Food Complement Unit
H2020	=	Horizon 2020
IBIS	=	Italian Bioregenerative Systems
ICC	=	Integrated Cargo Carrier
ISLSWG	=	International Space Life Sciences Working Group
ISS	=	International Space Station
LED	=	Light Emitting Diode
LEO	=	Low Earth Orbit
LGH	=	Lunar Green House
MEC	=	Modified Energy Cascade
MELiSSA	=	Micro-Ecological Life Support System Alternative
MPLM	=	Multi-Purpose Logistics Module
TAS-I	=	Thales Alenia Space – Italia
THESEUS	=	Towards Human Exploration of Space – a European Strategy
WG	=	Working Group
WP	=	Work Plan
WS	=	Workshop

I. Introduction

The human exploration of deep space and the colonization of other celestial bodies, the Moon and Mars, will require the use of a new generation of habitable space modules capable of supporting human life for long periods of time, with minimal recourse to the supply of vital resources from Earth[1].

The traditional life support systems are based on physical and chemical processes that provide different levels of integration and efficient control of the breathable atmosphere, water recycling and waste disposal. All current systems require significant regeneration of the active substances for the treatment of air and water and the constant supply of vital resources from the ground, to replace those lost from the cycles[2,3].

Bioregenerative life support systems (BLSS) are complex systems based on biological elements, such as higher plants, algae, microorganisms, which aim at recreating within confined spaces a biosphere similar to Earth's, ensuring the revitalization of the breathable atmosphere, with generation of oxygen and carbon dioxide fixation, the purification and recycling of water and moisture and the production of food for astronauts. In such an environment, higher plants and photosynthetic algae guarantee the production of biomass, including edible products for astronauts, while a combination of physical and chemical systems and bioregenerative processes based on micro-algae and bacteria provide for the generation of renewable resources from the waste products[4,5,6].

Within BLSS, as well as in the terrestrial ecosystem, the growth of higher plants plays a key functional role, for the production of food, release of oxygen and reduction of carbon dioxide, recycling of water, management of waste products. On the other hand, in confined environments and away from Earth, higher plants can play a positive impact also on the psychological well-being of astronauts. However, the cultivation of plants in confined environments and under reduced gravity conditions is extremely complex. Scientific knowledge on plants in space should be advanced, and several key technologies required for the cultivation of plants in space should be brought to a higher level of development and qualified for their use in the space environment[7,8,9,10].

Biological aspects which are the focus of research are related to the choice of the most suitable plant species to be grown in a space environment, the effects of absence of gravity or gravity reduction, and the effects of radiation or of the magnetic field on plant growth. Technological research focuses on the selection of substrates and more effective nutrient delivery systems; LED lighting systems with the most effective wavelengths; systems for monitoring the health of plants and decontamination; procedures to be adopted to ensure quality and safety of production from the point of view of astronauts' health and safeguarding the space infrastructure.

Another essential element of bioregenerative systems are bioreactors[11]. Colonized by microorganisms and maintained in proper operating conditions and optimal control, specific bioreactors can perform efficiently the basic functions of life support systems in space, complementary to those carried out by higher plants. Exploiting the great biodiversity of microorganisms, they offer the advantage of combining several functions that linked together allow the development of life support systems in a closed loop, in which the basic byproducts ("waste") from a bioreactor feed the processes of the next in the loop. Another significant advantage of bioreactors is that the basic processes occur in compact enclosures, where the basic physical and chemical parameters are controlled to ensure optimum operating conditions. A very accurate knowledge of processes taking place in bioreactors is necessary, to ensure a balance of mass and kinetic reactions.

In photosynthetic bioreactors, micro-algae or other edible microorganisms, such as the cyanobacterium Arthrospira, produce oxygen and food using light as the energy source and nitrate as a nutrient substrate. From the point of view of mass, volume and energy, they are more efficient than systems based on higher plants. Also from the point of view of nutritional characteristics, the cyanobacterium Arthrospira is comparable and "competitive" with food provided by higher plants.

A different category of bioreactors which is another critical link in the chain of bioregenerative technologies is that of the nitrifying bioreactors, which regenerate waste water, typically crew urine, transforming urea into nitrates by using bacteria. The dual function of nitrifying bioreactors is to produce drinking water for the crew and nitrate as a nitrogen source for photosynthesis of algae and higher plants. The nitrification process requires oxygen, that in a closed loop system can be derived from the process of photosynthesis. Both types of bioreactors, photosynthetic and nitrifying, require a carbon source, which can be obtained as a byproduct of the respiration of astronauts and regenerated for the production of vital substances for plants and humans.

As shown in References 1 to 13, a worldwide experience on BLSS has been generated since the beginning of the space era. In the last 25 years, the project MELiSSA (Micro-Ecological Life Support System Alternative), managed by the European Space Agency, has demonstrated several key features for the implementation of a complete BLSS[11,12,13]. The system is based on cycles of carbon, nitrogen and water, at a small-scale, adopting a proper selection of bacteria, algae and higher plants to regenerate vital resources and maintain the environment of space habitat in safe and favorable equilibrium conditions for human life.

Food, nutrients for plants, water and oxygen are produced by the system, starting from feces and urine, carbon dioxide and other organic byproducts. The MELiSSA system is organized in five compartments. Three contain bacteria that break down the waste products through a series of fermentation processes which liberate minerals such as nitrates, potassium, and calcium phosphates, in addition to carbon dioxide, which are essential for plant growth. The fourth compartment contains algae and plants that use the minerals and carbon dioxide via photosynthesis, resulting in glucose and oxygen for astronauts, the "consumers" of the fifth compartment.

Other projects being launched, funded by the European Commission, aim at the development and testing of technologies and procedures for the production of food in space environment, specifically the International Space Station and envisioned follow-up Space Exploration missions. One in particular, the just started EDEN ISS, involves the development of technologies essential to agriculture in confined environments and the development of a growing system housed in an International Standard Payload Rack, ISPR, on the ISS. The development and testing of the space system will be supported by a test phase in laboratory environment and then in the analogue harsh environment in Antarctica, where remote operations will also be demonstrated .

Other international studies, funded by ESA and NASA, provide for the development of concepts of space greenhouses in the lunar and Martian environments[14,15].

In summary, BLSS constitute an area of cross-disciplinary research showing renewed interest and rapid development. In this area there is a strong European scientific and industrial background and know-how. Within the space arena, the issue is related to human space exploration and colonization of the solar system. On ground, the issue is directly related and of interest for agriculture in confined and extreme environments and in the construction industry, with a very high space-to-ground transfer potential and with the expectation of a significant contribution to the issues of environmental sustainability, resource conservation, and energy efficiency. For these reasons, the BLSS theme is present in the agenda of the H2020 research program of the European Commission and in the Global Exploration Roadmap drafted by the International Space Exploration Coordination Group (ISECG).

II. The Italian background on Life Support Systems

The Italian background on Life Support Systems is represented by several spaceflight projects currently operating on the International Space Station (ISS) and on-ground Research & Development for exploration beyond the Low Earth Orbit (LEO), involving industry and academia, with funding from National and European space agencies, and private customers.

A. International Space Station (ISS)

The Italian contribution to the ISS, shown in Fig. 1, involves more than the 50% of the habitable volumes. Thales Alenia Space Italia (TAS-I) in Turin has designed and developed the ISS permanently attached modules Columbus (as co-Prime contractor with Airbus Defence & Space), the Nodes 2 and 3, the Cupola, the Permanent Multipurpose Module PMM and the Cargo Modules for the re-supply of the ISS, Multipurpose Logistics Module (MPLM) and the pressurized segments of the Automated Tranfer Vehicle (ATV) and of the Cygnus[16-23]. MPLMs, PMM[24] and, to large extent, Nodes 2 and 3, have been developed under the management of the Italian Space Agency. The Italian industry has contributed with various responsibilities to the ECLSSs of all the above modules. As well, national experimental payloads for the ISS[25], such as the animal endurance in space record-breaking Mice Drawer System[26,27], have contributed to the development of the national know-how in life support technologies and systems.

Since the early days, the primary national involvement in the ISS Program has allowed mastering the design, development, assembly, integration, testing, ground and flight operations of ECLSS, with a continuos flow of experience and lessons learned in new programs.

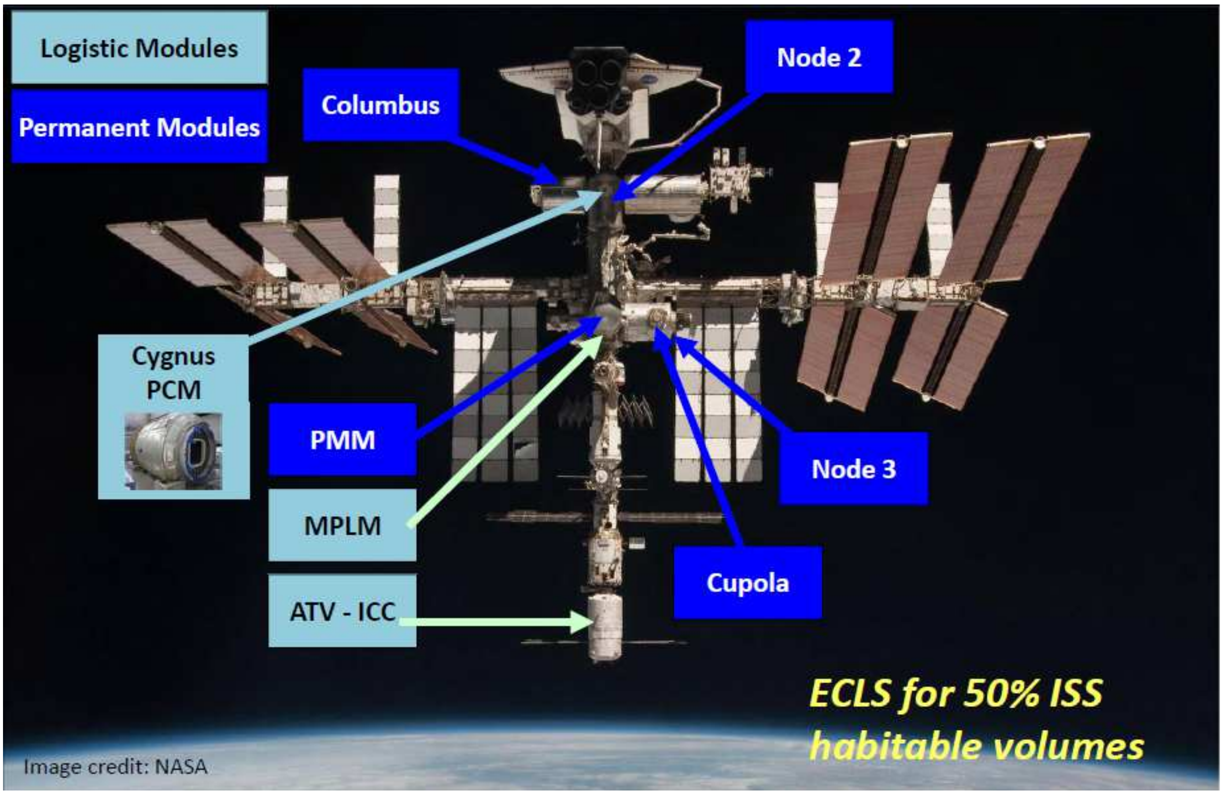

Figure 1. Italian contributions to ISS and relevant ECLS

ESA Food Complement Unit (FCU) Study

Under the ESA Study "ISS/MPLM for exploration", TAS-I was the prime contractor of the Food Complement Unit (FCU), carried on in 2007-2008[28]. The FCU (Fig. 2) is conceived as a rack-sized system dedicated to support plants growth and development in micro-gravity conditions, properly controlling the environmental conditions. The

resulting configuration is based on cultivation drawers for the growth of plants, including the substrate for the roots and the illumination system.
The overall design was focused on the realization of a system:

- Suitable for installation in the ISS
- Capable to provide up to a few percent of the overall nutritional value needed by one crew member
- Low resources demanding (including logistics and manpower)

And including a complex environmental control system, featuring:

- Control of the atmospheric gas composition (O_2, CO_2, trace gases and moisture content)
- Control of the atmospheric conditions (temperature)
- Control of the illumination conditions to support photosynthesis (spectral composition, intensity, photoperiod)
- Control of water and nutrients delivery.

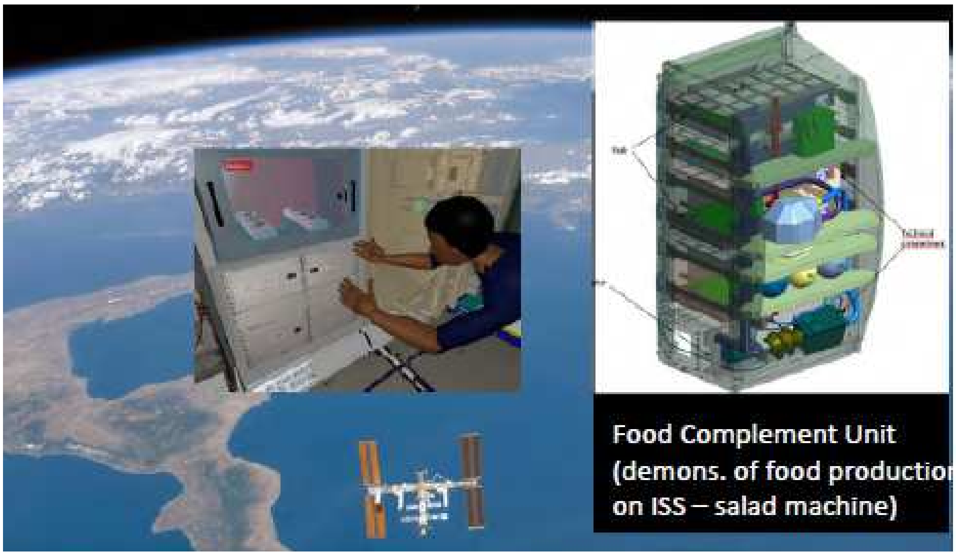

Figure 2. ESA Food Complement Unit (FCU) Study

B. BLSS R&D

In terms of on-ground Research & Development for exploration, we have to mention first the Bioregenerative Life Support program Controllo Ambientale Biorigenerativo (CAB), a key element of the ASI Medicine & Biotechnology scientific program Activity Plan 2006-2008[29-32].
The objective of the CAB project was to define and prepare the elements needed to setup a controlled biological system, allowing the regeneration of resources and the production of food for life support in long duration missions. Within the project a feasibility study, functional specifications, a development plan and a preliminary architecture were produced for the following technological demonstration. The project included:

- Higher plants as basic elements for food and oxygen production, CO_2 regeneration and water purification via the photosynthetic and leaf transpiration processes
- Biological & physico-chemical systems for environmental control, monitoring, power & data distribution, etc.

The sectors of concern and key players are shown in Fig. 3.

At the time of the CAB program, Italy started collaborating with MELiSSA, in a synergistic and complementary fashion, with activities on Food Characterization and the Pilot plan including the participation of Academia (The Department of Agricultural Sciences of the University of Naples Federico II) and Industry (Enginsoft).

Figure 3. Key elements and actors of the CAB Program

Lunar Green House (LGH) Project

The University of Arizona Lunar Greenhouse (LGH) project features a collaboration with Italian industrial and research actors[33-37]. The project is mainly aimed at the design, manufacturing and testing of a lunar greenhouse prototype (Fig. 4). Since 2010 the project has been supported by NASA Ralph Steckler Space grant for two distinct phases.

During Phase I, TAS supported the project working on energy flow Modified Energy Cascade (MEC) modelling, with the data obtained from the closure experiments.

In Phase II, TAS enhanced the space-oriented insight into the LGH design (system integration), studied liquid streams within the composter or alternative technologies, upgraded Phase I's modified MEC predictive model (failure analysis), evaluated LGH metric via Equivalent System Mass (ESM).

Figure 4. Lunar Green House prototype at UoA

In 2011 an international USA-Italy cooperation project co-funded by the Italian Ministry of Foreign Affairs aimed at the design and development of an inflatable greenhouse for plants growth, food production and life support in space, coordinated by the Italian National Research Council, in collaboration with the University of Arizona.

III. The IBIS Working Group

In order to cultivate the national know-how in the field and strengthen the Italian position at the international level, it became necessary to create a network of contacts and provide a forum for the exchange of information and ideas and the same time undertake a series of actions that could stimulate and encourage research initiatives, technological and commercial development on the subject.

With this goal, the Italian Space Agency has established and coordinates a national working group on bioregenerative systems, named IBIS (Italian BIoregenerative Systems), which collects the contribution of the most advanced scientific and industrial national experts in the field.

C. Scope and Objectives

The scope of the WG can be summarized as follows, in relation with past, present and future:

	Facts	Goal
Past: Background	Diversified and multidisciplinary know-how in a highly innovative and rapidly developing sector Several R&D areas, players, contexts	Preserve and foster
Present: On-going activities	Several parties involved: universities, research institutions, industries, SMEs Diversified R&D areas	Integrated approach and coordination
Future: Up-coming opportunities	Interesting opportunities for development exist both in national and European frameworks	Coordinated participation to increase chances and maximize returns

In summary, the IBIS WG aims at creating and organizing a national network of stakeholders, creating technical and programmatic databases and a forum for exchange of information and ideas, identifying and carrying on specific actions for fostering R&D, spin-offs, and commercial initiatives on the subject. The IBIS WG:

- Shares information on funding opportunities as a distributed net and open forum
- Surveys science and technology state-of-the-art and national heritage and know-how, generating a catalogue of national technologies and scientific research capabilities
- Identifies «dual» goals (space/terrestrial applications), delivering projects and plans
- Elaborates strategies and roadmaps for Space Exploration, Sustainability and Green Economy
- Promote events, dissemination and outreach.

D. Organization and Membership

The WG is chaired by an ASI representative, currently Salvatore Pignataro, supported by Scientific and Engineering Coordinators, presently Prof. Stefania De Pascale of Univ. di Napoli and Cesare Lobascio of TAS-I (Fig. 5).

Members of the WG are representatives of Italian Academia, Research Centers, Industry, including Small Medium Enterprises (SMEs).

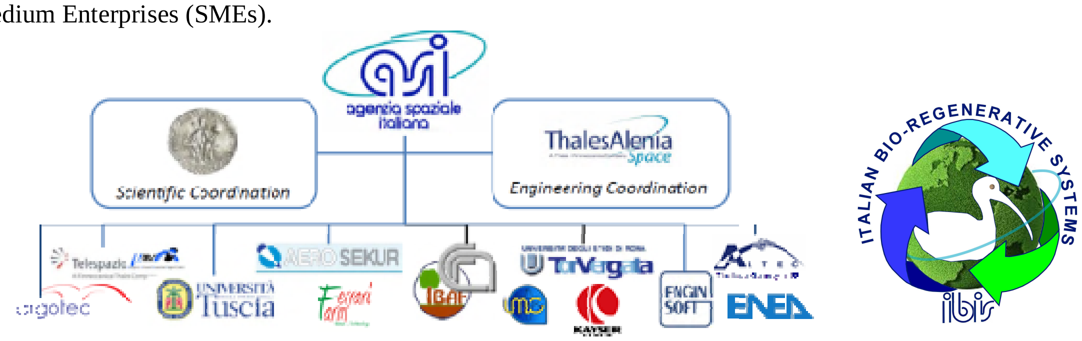

Figure 5. The IBIS WG Organization, key stakeholders and logo.

Participation is open to those groups participating to ESA, EC or National space BLSS programs. Upon request, non-space actors can be admitted and invited to contribute to the IBIS WG.
A concise Term of Reference has been agreed among the parties to document objectives and scope of the working group and to regulate the memebership.
As well, the working group has developed an IBIS WG logo shown in Fig. 5.

E. Ongoing Activities

The Working Group is currently engaged mainly in three domains:
- Projects and Proposals – facilitating the start-up of new ESA projects; defining themes and proposals to the calls of the European Commission in the framework of the H2020 Program
- Dissemination and Outreach - with a series of publications on the website of the Futura Mission Outpost 42, involving the Italian astronaut Samantha Cristoforetti
- BLSS Roadmapping – supporting ASI for the organization of an International Workshop on Bioregenerative Systems that will be hosted in May 2015 at ALTEC premises in Turin, with the goal of proposing a roadmap and contributing to the formation of a national vision in the medium and long term on the bioregenerative theme.

1. Projects and Proposals

At Ministerial Conference in 2012, Italy significantly increased the contribution to the MELiSSA Project, stimulating a wider participation of Italian players in this key BLSS program that in 2014 celebrated 25 years of successful activities. On the basis of heritage and competences, integration needs and opportunities of synergy with on-going projects, an integrated and organized Italian participation was considered appropriate, focusing on theme of Higher Plants. The key R&D topics of the Italian CAB program were recollected as:
- Crops selection and modeling
- Hydroponics & nutrient delivery system
- Energy saving, CFD and illumination
- Monitoring and sensors
- Food quality and processing

On this basis, the target contributions that Italian groups could provide, increasing the MELiSSA cooperation with existing actors, have been identified as:
- Phase A of a Precursor Food Production Unit and Engineering of Atmosphere Subsystems
- Refurbishment and characterization of the Higher Plant Compartment within the MELiSSA Pilot Plant
- Development of filtration systems in the Fiber Degradation Unit

In line with the ASI approach for contributing to the MELiSSA overall objectives through subscriptions, the IBIS WG works at improving coordination and engagement on bioregenerative activities within Italy, encouraging eligible Italian parties to candidate for entering the MELiSSA consortium.

The European Commission program Horizon 2020 (H2020) is the European framework program for research and innovation covering years 2014 to 2020. In the space domain, it prepares for the increasing role of space in the future and reaps the benefits of space now. The Work Program 2014 – 2015, with the goal of leadership in enabling and industrial technologies, for space issued the call “Competitiveness of the European Space Sector: Technology and Science”[38], including two relevant competitive actions:

– COMPET 7 - 2014: Space exploration – Life support, on closed loop regenerative life support system technologies

– COMPET 4 - 2015: Space exploration – Habitat management, on safe and reliable quality control of indoor environment, in particular from a biocontamination perspective.

Under the upcoming Work Program (2016 – 2017), ASI provided inputs including recommendations for following-up with space demonstration activities started within WP 2014-15 and for developments of analogues.

Distributing and sharing of information among the WG membership has encouraged the national participation to international proposals to the EC calls.

Within the International Research Announcement for Research in Space Life Sciences at the International Space Station (ILSRA-2014), the project WAPS (Water Across the Plant Systems: effects of microgravity on organ morphological and functional traits), proposed by a project team led by the University of Naples, one of the IBIS WG coordinators, has been positively evaluated. The general aim of the experiment proposed for the ISS laboratory is to evaluate the effects of microgravity on morphological and functional traits of plant organs with specific reference to the water flow pathway from roots to leaves. Proposed actions are designed to decouple the direct effect of microgravity on cells and tissues from the indirect effects caused by restricted free air convection on plant life cycle from embryonic development to the first stage of adult organ systems.

On a national basis, the so called "Progetti Premiali" will include a national call for studies on Exploration Scenarios, with BLSS as one of the key topics, together with inflatable systems and radiation protection. Pending ministerial approval, the 2015-2017 ASI three-year budget envisages further funding within the Human Flight Office for exploration activities, including follow-ups on Bioregenerative studies.

2. Dissemination and Outreach

The ASI management requested the IBIS WG to contribute with ideas for the Education and Public Outreach (EPO) for the Futura Mission on the ISS, with Italian astronaut Samantha Cristoforetti, which focuses on nutrition.

This has been accomplished via:

- EPO HIP (Higher Plant & Trend), as a complement to the ESA EPO Spirulina, promoting healthy eating on Earth and in Space, via the experience of seed germination in simulated microgravity and in 1-g (with contributions of UniNA, UniMI, UniSS, Argotec)
- EPO scripts: Green Earth from Cupola (TAS-I), Exobiology (UniTV), PSS (INAF-OAC)
- Avamposto 42 (http://avamposto42.esa.int) contributions, including short educational articles on BLSS activities, under a specific additional section "Bioregenerative Systems", Fig. 6.

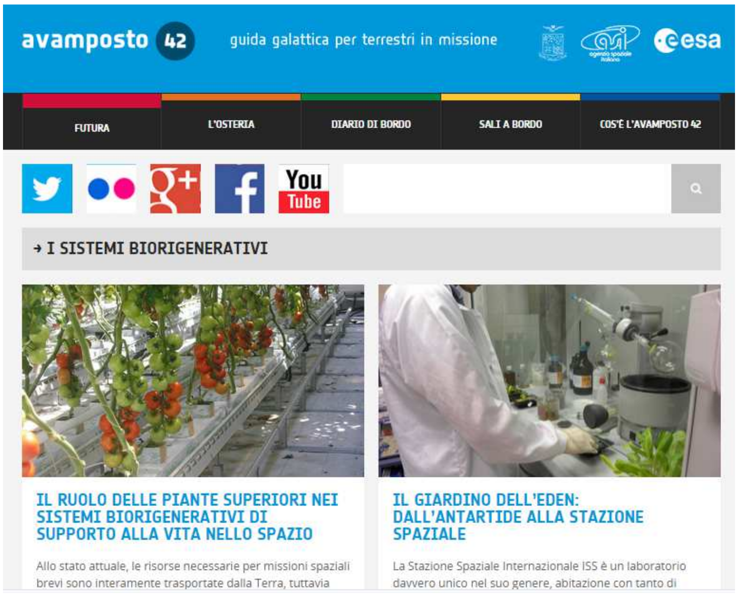

Figure 6. The Avamposto 42 web site at avamposto42.esa.int/blog/categoria/futura/gli-esperimenti-di-futura/i-sistemi-biorigenerativi

3. BLSS Roadmapping

The International Space Life Sciences WG (ISLSWG) organizes regularly dedicated workshops with the goals of reviewing international research progress, with special regard to gravity-related phenomena in a specific research area, to define critical scientific questions in that research area and to determine the relative importance of these questions, as per ISLSWG Strategic Plan. The ISLSWG decided to dedicate the 2015 WS, to be held in Italy (Torino), to the topic of BLSS.

A previous International Workshop on Bioregenerative Life Support was held in Torino (Italy) in 2006 under the CAB Program, with representatives from Universities, Research Centers, Industries, and Agencies.

The goals were:

- Determining the state of art and trends in BLSS around the world
- Identifying the main scientific and technological needs with related criticality/priority
- Defining possible lines of collaboration within the national and international programs and facilities

Four Working Groups worked on Systems & Architectures, Biological elements, Demonstrators, Regenerative Technologies, identifying 33 technological and scientific needs.

With broader perspectives and experts participation, the EC funded THESEUS: Towards Human Exploration of Space – a European Strategy[39], a Coordination and Support Action under the 7th Framework Program.

THESEUS developed an integrated life sciences research roadmap enabling European human space exploration, in synergy with the ESA strategy, taking advantage of the expertise available in Europe and identifying the potential of non-space applications and dual research and development. The experts Cluster 4, on Habitat Management, worked on:

– Microbiological quality control of the indoor environment in space (identifying 4 Key Issues)

– Life support: management and regeneration of air, water and food (8 Key Issues)

covering life support for self-sustainability via regenerative processes using physical, chemical and biological technologies:

– air revitalization (CO2 removal & O2 production),

– water supply and recycling,

– food supply (plants, microbial),

– waste management (removal & recycling).

Why another workshop? Because the need was felt to:

• review and update work items, players, key issues identified at the CAB WS and by the Theseus Project

• define follow-up plans, identifying the potential of non-space applications and dual research and development

• define top-level requirements for dual research and development projects

• identify and possibly establish areas and structures of international co-operation.

The WS, coordinated by ASI and DLR and supported by the IBIS WG, will be held at ALTEC premises in Torino on 18-19 of May, 2015, with more than 40 oral contributions from participants designated by the ISLSWG member Space Agencies.

F. Methods and Tools

The Terms of Reference define the goals, methods and tools of the IBIS WG.

The WG holds:

- Face to face meetings on specific occasions, biannually. The first meeting was held in April 2013 at ASI in Rome, then December 2013 in Turin; May 2014 in Sperlonga, November 2014 in Leiden;
- Plenary teleconferences, bimonthly;
- Regular coordination via weekly tag-ups of the Chair and coordinators (ASI, UniNA, TAS-I), since Oct. 2013.

Communication tools include a teleconferencing tool, an ECM community for sharing documents, the Linked-In group «Agrospace Friends» and, in the near future, a dedicated Facebook page.

IV. Conclusions

BLSS is a multidisciplinary theme, rapidly developing in the international arena and presenting a robust scientific and industrial background in Italy: life support systems for the ISS modules and ground based R&D towards space exploration.

Since BLSS is one of the key assets in H2020, the Global Exploration Roadmap and ESA and ASI roadmaps, it was deemed appropriate to create a national network of stakeholders, a forum for the exchange of information and ideas, and to initiate and coordinate specific actions that could stimulate and encourage research, industrial and business initiatives on the subject.

The IBIS Working Group has been established bringing together the scientific and industrial experts on the subject, also through the organization of specific national and international events; to encourage the exchange of ideas and information; and to contribute to the formation of a national vision for the medium and long term.

The Working Group is mainly engaged in three domains:

- Projects and Proposals – facilitating the start-up of new ESA projects, defining themes and proposals for the calls of the European Commission in the framework of the H2020 Program;
- Dissemination and Outreach - with a series of activities such as those involving the Italian astronaut Samantha Cristoforetti and publications on the website of the Futura Mission, Outpost 42;
- BLSS Roadmapping – supporting ASI for the organization of an International Workshop on Bioregenerative Systems that will be hosted in May 2015 in ALTEC in Turin with the goal of proposing a roadmap and contributing to the formation of a national vision in the medium and long term on the bioregenerative theme.

Future activities will include elaborating the results of the International Workshop on Bioregenerative Systems, pursuing the lines of action most representative for Italian players within International collaboration schemes, under the available funding opportunities granted by EC, ESA and ASI, and regional institutions. The WG will also encourage parallel commercial developments and continue disseminating results via outreach actions.

Acknowledgments

We acknowledge all the members of the IBIS WG, listed on the Terms of Reference, and in particular R. Fortezza (Telespazio) for developing the IBIS WG Logo.

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