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DIGITAL SCIENCES FOR BIOECONOMY OF WASTES, WATER AND NUTRIENTS

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Abstract— This paper presents the ANUMAB project – "Approches numériques et mathématiques appliquées pour la bioéconomie et la REUSE". This project, under the patronage of the UNESCO International Water Center ICIREWARD in Montpellier aims at i) proposing the creation of a UNESCO chair on the valorization of wastewater, waste and nutrients at ENIT-LAMSIN, Tunisia, ii) creating a new research theme within the SIMEV UNESCO chair in Montpellier and iii) beginning research activities through the reinforcement of collaborations by relying on the network of collaborations federated within the Euro-Mediterranean research network TREASURE – "Treatment and sustainable reuse of wastewater in the Mediterranean rim". The main originality of the project lies in the fact that it advocates the adoption of an integrated multidisciplinary approach to meet the challenges of the circular economy.

Keywords— Circular economy, wastewater and organic waste valorization, nutrient recycling, water reuse, UNESCO chair

I. INTRODUCTION

Resources are becoming scarce. Population and economic growth have led to a higher demand for resources, which puts more stress on their supply and the environment. Especially water resources are under great stress, whose demand is estimated to increase by 50% in the next five-ten years. Therefore, the reuse of resources is becoming more and more attractive towards a circular and self-sufficient bio-based economy, [1]-[3].

Water, besides being a resource on its own, is a transport medium for other resources. Materials, chemicals and energy are added to water by households and businesses when they use drinking water and produce wastewater. Thus, the water chain has many opportunities to recover resources and close cycles [4].

Most of the actual policies to push forward circular economy are limited either to energy recovery, the extraction of molecules of interest from waste, the recovery of nutrients or the reuse of water. In other word, very often, only one specific objective is pursued and an unified viewpoint is not adopted: very few approaches include neither an unified view involving a pluridisciplinary panel of experts neither a multi-criteria considerations. In the ANUMAB project ("Approches numériques et mathématiques appliquées pour la bioéconomie et la REUSE"), we aim at adopting such an "integrated" approach in mobilizing a very large panel of experts. To do so, it is obvious that we need a common language without which we cannot exchange in a constructive and common way. Within the ANUMAB project, we claim that putting the modeling and control tools in the center of the project precisely allow all its experts to exchange on a common basis, share common definitions of the involved entities and components and may really integrate the whole within an integrated and pluridisciplinary framework. In addition, modeling and control tools fundamentally address dynamical questions that are fundamental within the circular economy of wastewater, waste and nutrient while they are usually neglected when traditionnaly addressed. The project proposes a paradigm shift to consider wastewater, the nutrients it contains and waste as new resources to be processed to meet needs/usages. To do so, it is necessary, on a given territory, to inventory resources (liquid/solid) and needs/usages (liquid/solid) – that are dynamic as underlined hereabove - and to develop processing systems that can connect these resources and needs under sanitary and environmental constraints. This approach is illustrated in figure 1. Without prejudging of the existing regulations, it is a fact that the uses (demand) can be of very diverse natures and

dynamic (depending on the seasons/weather/uses) it is thus very important to think of "flexible processing systems". By flexible, we mean systems capable of adapting over time the treatments of the available liquid and solid resources to treat them on demand and supply quantities of treated water and/or solids to the various stages. A step further to this new way of pushing forward bioeconomy is to be able to anticipate these specific needs – for instance such quality and quantities of waters in the next days - by using measurements or estimations of nutrients and water needs and to process wastewater in such a way to indeed be able to provide such treated water. In other words, our capability of feedback

specifications to the processing flexible systems, hereabove qualified as "flexible", allows us to use the action levers available within these treatment/processing systems to deliver material processed according to specifications. And thus the importance of control theory that precisely aims at feedbacking information provided by sensors to act on a system to stabilize it or making some variable to follow a – possible time-varying – "setpoint". This way of thinking the treatment of liquid/solid waste to adapt the quality of the treated matter to usages will be called here the "treatment on demand" concept.

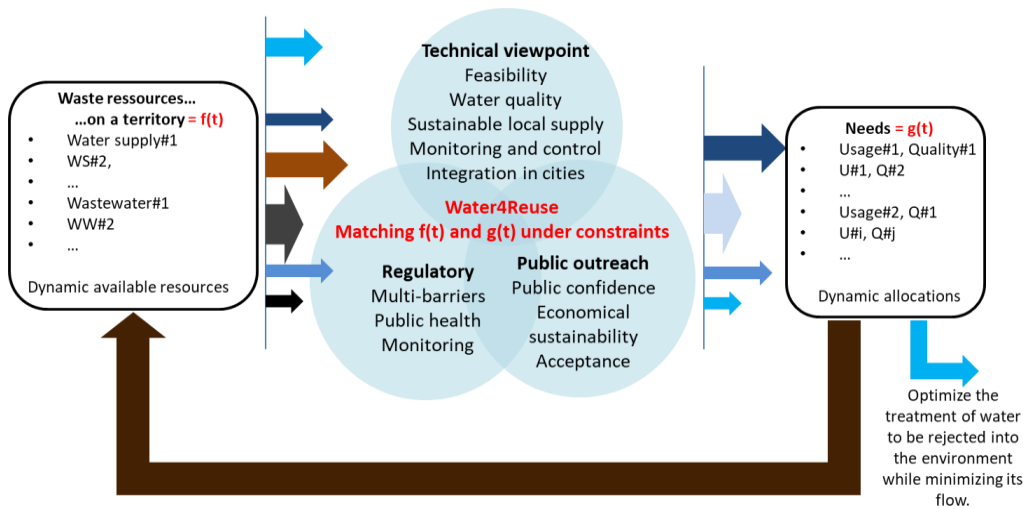


Figure 1: Schematic representation of the "treatment on demand" concept promoted within the submitted COST action Water4Reuse for the valorization of wastewater

Notice that these ideas may be implemented in alternative ways by considering new approaches called source separation or by using decentralized systems precisely because they are very flexible. Using such systems, it would be possible to "treat on demand" a given quantity of water with a given quality for a given usage in a given location". This alternative is schematically represented in Figures 2a and 2b where we can visualize the past and future situations with their respective drawbacks and advantages with respect to bioeconomy:

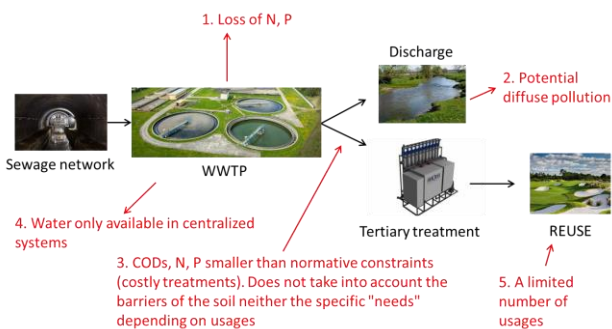


Figure 2a: Past/actual situation with its drawbacks



Figure 2b: A possible updated configuration together with its potential advantages

II. THE ANUMAB PROJECT

A. A new paradigm for valorizing wastewater

In the present project, although generically proposed to valorize both wastewater and solid waste, we concentrate in a first step on the valorization of wastewaters - and nutrients they contain - within the Mediterranean Rim. Modern wastewater treatment plants (WWTP) are designed to deliver

a constant quality of treated wastewaters that are rejected into the environment when they comply with normative constraints. Within the actual interest for circular economy, there is an increasing concern with nutrient recycling (e.g. N and P). Assuming we can treat wastewaters in such a way we control sanitary risks (related to the potential presence of pathogens in the raw wastewaters) and environmental risks (related to the potential presence of a number of undesirable compounds such as micropollutants, for instance), we can think of ways to operate treatment systems such that to keep nutrients in the treated wastewaters while managing dynamic constraints of resources and demands. These nutrients are beneficial for plants/crops: within a water reuse chain, the nutrients brought to the plant via treated wastewater are nutrients that do not need to be brought via conventional fertilization using chemical fertilizers. This idea is in line with the concept of «treatment of water on demand» - represented in Figure 1 - which consists in treating the water such that the quantity and the quality of waters are exactly those needed for a specific usage. For an agriculture use - but the concept can also be applied in an urban or even industrial context for other usages - this means that the quantity and the quality of waters provided to plants match exactly their demand. In general terms, it means that we must go from a situation where the wastewater is a product to be treated for finally being rejected into the environment - putting into the system a great quantity of energy and producing a high quantity of waste - to a situation where the wastewater is a resource to be processed - if possible in an optimal manner in order to maximize circular economy indices and minimize costs and ultimate waste - to match specific demands and needs while maximizing nutrient/energy/water recycling. Such facilities are now called WRRF for waste resource recovery facilities. While it has been proposed a quite long time ago, it has not really been put in practice. On a given territory, this question is not decoupled from the management of organic solid wastes since such wastes can be used in agriculture as a nutrient source. We can illustrate these ideas in comparing Figures 1 and 2 representing schematic representations of a classical wastewater treatment plant (WWTP) and a waste resource recovery factory (WRRF).

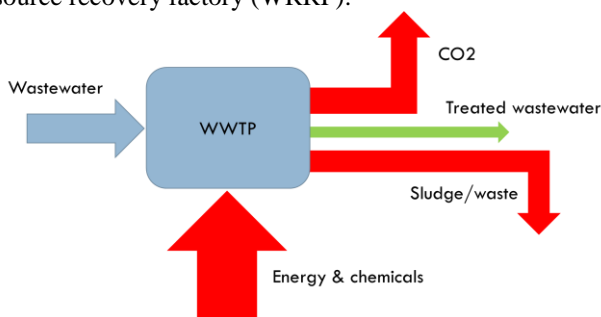


Figure 3a: Schematic representation of a classical WWTP

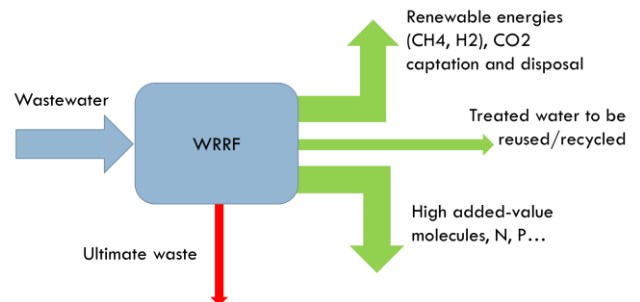


Figure 3b: Schematic representation of a classical WRRF

In a classical WWTP, we put a lot of energy and spend a lot of money to remove nutrients and pollutants from wastewater to produce CO₂ and sludge which we cannot control the quality. The final product of this plant is the treated water that is released in the environment. In a WRRF, energy needed for the functioning of the plant is recovered from the resource - the wastewater - to be processed. As long as possible, high added value molecules are produced or, as nutrients, kept in the treated water to be used in agriculture. The impact of a WRRF is supposed to be much less important than of a WWTP since the remaining pollutants are removed in taking advantage from the epurating capacity of the transport or storage systems or from agronomic soils without additional costs.

These questions are at the heart of the ANUMAB project dedicated to the development of modeling and control approaches to promote a systematic and feasible approach to the optimization of waste, water and nutrients management on a given territory, and under sanitary and environmental constraints to contribute to the main challenges of circular economy.

To push these ideas forward circular economy, this project, under the patronage of the UNESCO International Water Center ICIREWARD in Montpellier (<https://fr.unesco-montpellier.org>) aims at i) proposing the creation of a UNESCO chair on the valorization of wastewater, waste and nutrients at ENIT-LAMSIN, Tunisia (<http://www.edsti.enit.rnu.tn/fr>), ii) creating a new research theme within the SIMEV UNESCO chair in Montpellier (<http://www.unesco-simev.org>) and iii) beginning research activities through the reinforcement of collaborations by relying on the network of collaborations federated within the Euro-Mediterranean research network TREASURE - "Treatment and sustainable reuse of wastewater in the Mediterranean rim" (www6.inrae.fr/treasure) and on the French national network on REUSE (www6.inrae.fr/reuse).

B. Social and juridic sciences

The solutions to be implemented for the reuse of water and the recovery of waste require the support of citizens and therefore raise questions of social acceptability. In addition, potential solutions for recycling and reuse require the mobilization of new technologies allowing the production of products (water, molecules of interest) at excellent quality levels. In addition, alternatives such as source separation or

new uses of water, especially in cities, challenge traditional recycling and reuse schemes. However, these technologies cannot be implemented because they are constrained by regulations and legislation justified more by precautionary principles than by a rational approach justified by scientific knowledge. That is why, in the ANUMAB project, we frame the issues we address from a legal perspective and work with legal experts to evaluate current regulations. In particular, we benefit from the investment in the project by experts from countries where REUSE has been developed for a very long time. In the light of this expertise, we envisage what the evolutions of the French and European regulations could be. The current French regulation is based on the availability of treated wastewater. In other words, it is water that has already been treated to be released into the environment: it is therefore precisely of a quality required to be released into the environment but not in conformity with a particular use, for example to be reused in agriculture where it would have been necessary to preserve the nutrients that were present before treatment... This new approach of considering wastewater - and not treated wastewater - as a new resource, leads us to revisit all current regulations and consider how they could evolve to take into account this new reality. The first results of this kind of study will be presented at the seminar: "Réutilisation des eaux usées traitées : premières analyses interdisciplinaires du règlement UE 2020/741 du 25 mai 2020" to be held in Narbonne on March 11, 2022 (*cf.* the website of the REUSE network and [5]).

III. A NEW UNESCO CHAIR AT ENIT

A. ENIT-LAMSIN and UNESCO: a long story

One of the main deliverable of the ANUMAB project is the creation of an UNESCO chair on the valorization of wastewater and waste in Tunis. ENIT-LAMSIN has a long story with UNESCO. Although inactive today, the "Mathematics and Development" Chair, held by Mohamed Jaoua, former director of LAMSIN, was active from 2003 to 2012. As conceived by its holder, the UNESCO Chair was intended to be a space for reflection and promotion of applied mathematics at both regional and national levels. Throughout its life, the Chair has organised numerous schools and promoted training in mathematics, thus propelling Tunisian mathematics into an international dynamic. Through its participation in large-scale international projects, such as the Sarima project (Support for Research in Computer Science and Applied Mathematics for Africa), for which Amel Ben Abda, Professor at ENIT and member of LAMSIN, was responsible for the Maghreb, LAMSIN has become a leading player in mathematics in Africa. In the wake of this project, LIRIMA (International Research Laboratory in Computer Science and Mathematics for Africa) was created, a "laboratory without walls" co-sponsored by the ENIT and INRIA. Two Tunisian project teams have been set up within the framework of this project: EPIC (2011-2014) and Epicard since 2015. The Unesco Chair has been animated by thematic semesters - five over the period 2004-2007 including the

semester "Mathematics for Life Sciences" (in 2007), coordinated by Claude Lobry (Univ. of Nice, one of the founders of TREASURE) and Slimane Ben Miled (ENIT-LAMSIN) as well as several seminars and conferences for the general public involving international personalities. The echo of the Chair still resonates through the LIRIMA, already mentioned, but also the CREMMA and especially the "Minds" department of the ENIT, which is fully supported by the skills of LAMSIN.

Today, through this project, LAMSIN wishes to relaunch and develop a new UNESCO chair on "the valorization of water and waste". This will aim at pushing national training and research in applied mathematics to the management and the optimization of water and waste in close collaboration with the partners of the TREASURE network and under the aegis of the ICIREWARD UNESCO Centre in Montpellier.

B. Strong North-South and South-South collaborations

The ANUMAB project is part of a partnership that has been established for nearly 20 years between the partner researchers around the issues of modelling and control of living organisms. As mentioned above, the partnership has evolved over time and is now formalised by the TREASURE Euro-Mediterranean scientific research network led by INRAE. It has been structured around institutional actions, sometimes led by the University of Montpellier (AVERROES exchange programme), INRIA and IRD (STIC Tunisia 2008-2009, 2009-2010, 2013-2014), INRAE (incentive projects, REUSE national network), several European projects and initiatives (IRSES COADVISE project, JPI Water Control4Reuse) or bilateral Hubert Curien projects (UTIQUE 2013-2015, TASSILI 2015-2018, TOUBKAL 2017-2019)... It is very active in terms of training via the regular co-organisation of scientific seminars and research schools, often with the support of CIMPA or the UNESCO chair SIMEV. The INRAE REUSE network is also very active on the Montpellier scene via MUSE and particularly the KIM Waters (organisation of an international colloquium in 2019, obtaining post-doctoral fellowships on REUSE, support for mobility obtained this year precisely to broaden the contours of the network internationally, support from the AGROPOLIS foundation via several research projects).

IV. PROJECTS ON WHICH THE NEW UNESCO CHAIR CAN BUILD: HUMAN AND MATERIAL MEANS

To develop and grow, the project may count on a number of past, actual and submitted research projects.

A. Control4Reuse project

The Control4reuse project (supported by the JPI Water program 2017) aims at developing methods and tools to propose a new paradigm for adapting the quality of treated wastewater to crop's needs. The adopted scheme is represented in Figure 4 following the systemic classical approach adopted in modeling and control theory. The problem is to consider "action levers", also called actuators through which we can act on the system (the WRRF). The

idea of the project is based on the fact that, taking advantage of weather forecast, we are able to use crop models to predict the future productivity of the culture together with the dynamic needs of the plant. When such models are available a classical control approach would consist in coupling WRRF and plant models: the – non controlled - inputs of the system are the wastewater characteristics and the weather forecast. The control input vector is the set of available action levers (actuators): these are typically aeration powers, valves, recirculation or withdrawal sludge flowrates... The output

vector of the system is the set of dynamic states, some of which being of particular interest from a control performance point of view. For instance, the crop model may be used to predict crop productivity... However, since the corresponding models are of different nature - they have not been developed by the same communities of researchers and they do not content the same variables, they are very difficult to couple. An alternative chosen within the control4reuse project is described hereafter.

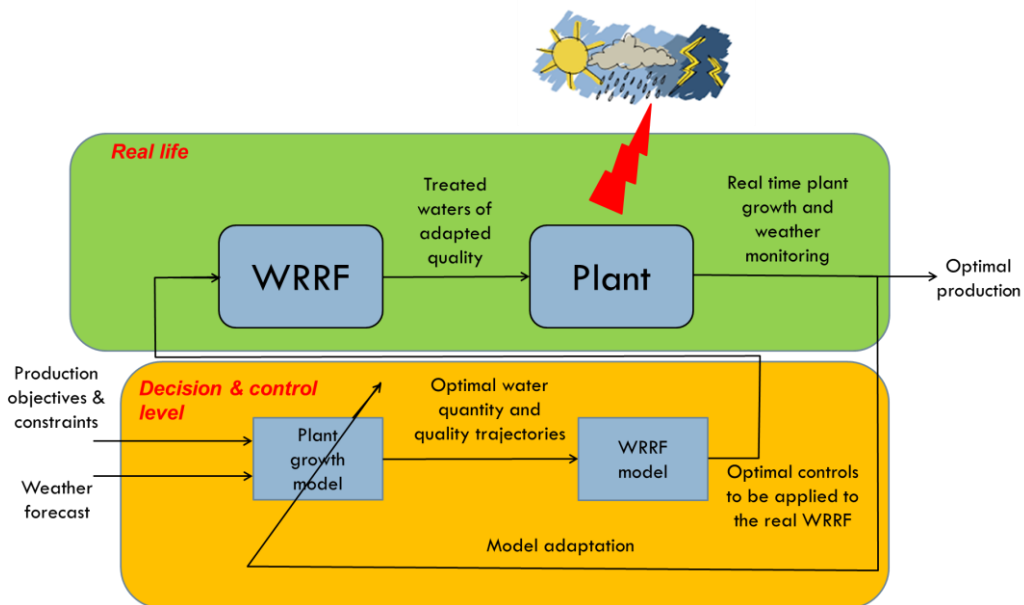


Figure 4: Schematic representation of the "treatment on demand" concept for the valorization of wastewater

In this scheme, both crop and WRRF models are used but are not directly coupled. Instead, the crop's model is used within an optimal control problem to generate setpoints for the WRRF. More precisely, let us assume we aim at maximizing the biomass produced. First, given the most probable climatic scenario, we consider the crop model and

we solve an optimal control problem where we compute the optimal nutrient and water trajectories to maximize the biomass produced. Such a new paradigm may be represented in Figure 4 while its application in practice is schematically represented in Figure 5.

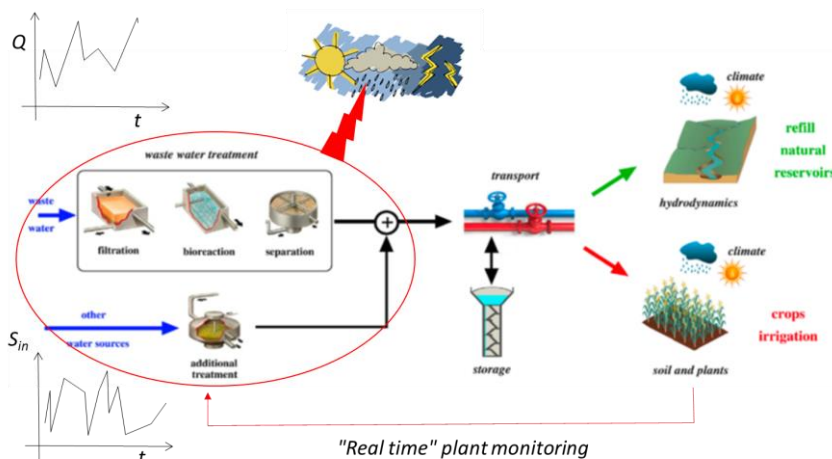


Figure 5: Taking advantage of the lever actions available at treatment plant stage in taken into account the feedback information available at the usage stages as proposed in [6].

Which WRRF could be used to modulate treated water quality, that is the content in terms of the different forms of nitrogen (ammonium, nitrite and/or nitrate)? Such a system must include nitrification, denitrification and denitrification capabilities. Such a flexible system has been proposed within Farouk Aichouche's PhD thesis prepared within the Control4Reuse project, *cf.* [7]. It is a process made of several biological tanks interconnected by valves and pumps. Notice that depending on the position of a number of valves, the process allows the treatment of the nitrogen and to control its different forms through the use of available actuators (input flow rate, recirculation flowrates, waste sludge flowrate, etc...), illustrating the notion of flexibility required in the integrated approach proposed. Within Control4Reuse, alternatives have been proposed using other treatment configurations, such as the well known BSM1 model, *cf.* [8].

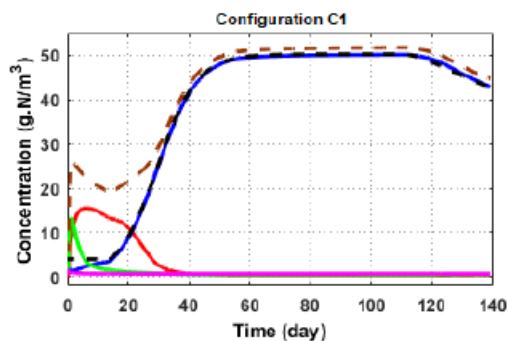


Figure 6: Example of results obtained within the Control4Reuse project - Optimal setpoint (black dotted line) and dynamic trajectories of the nitrogen forms (in red, green, blue). The nitrate trajectory follows very well the optimal nitrate setpoint which represents the optimal needs of the crops computed with the crop model.

B. The French National Research Network on REUSE

The INRAE network – or the French National Research Network on REUSE - has emerged from the fusion of former IRSTEA and INRA institutes. It exists from January 2020, when the fusion has been effective. It aims at federating research activities on REUSE within INRAE and with its collaborators. It informs and provides expertise to help decision makers relatively to the valorization of wastewater. It is a pluridisciplinary research community dedicated to push forward the integrated approach described hereabove. It is structured in 4 "research themes" (Territories, integrated REUSE chain, Risks and stakeholders) and 4 "application domains" (urban REUSE, rural REUSE, industrial REUSE and REUSE for southern countries). Several seminars and research schools are regularly organized. Researchers of the network also regularly submit projects that are coordinated by the network, as for instance the already mentioned COST Water4Reuse initiative recently submitted. Finally, researchers of the network coordinate several experimental sites allowing us to promote research results in practice.

C. The Euro-Mediterranean TREASURE Research Network

TREASURE (for Treatment and Sustainable Reuse of Effluents in semiarid climates) is a scientific Euro-

Mediterranean research network associating research labs and researchers from Southern Europe and Northern Africa countries about biological wastewater treatment plants and microbial ecosystems. At its origins, in 2006, the involved partners only consisted of academics from France, Algeria, Italy and Tunisia. Today, depending of the running project and of the institutions which support it, it is a network of a dozen partners of both Northern and Southern Mediterranean countries. The network aims at promoting both research and education activities, the improvement and the diffusion of knowledge on bioprocesses and microbial ecosystems – notably through co-advising of PhDs – being among the main components of the project. International scientific seminars are regularly organized together with workshops and schools (*cf.* www6.inrae.fr/treasure).

V. CONCLUSION

The main objective of the ANUMAB project is to push forward a new paradigm consisting in considering wastewater and waste as new resources to be processed "on demand" by new flexible systems. To do so, an integrated approach is promoted including not only engineering sciences but also social, economic and juridic sciences.

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