The European Network “Water2020”: a novel approach multi-stakeholders for the sustainable technological development in municipal WasteWater Treatment Plants (WWTPs)

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Abstract

The authors present an experimental research newtorked within the European Cost Action ES1202 "Water 2020“ (www.water2020.eu). The collaboration between the Research Group of University of Verona and Alto Trevigiano Servizi, an Italian Public-owned Water Utility, permitted to develop the first demonstration a full-scale application of the S.C.E.N.A. process, the biological removal via nitrite of nutrients (N, P) for high load wastewater through the valorization of the sewage sludge, while optimizing energy consumption, lowering greenhouse gas emissions and minimization of chemicals . A modified SCENA process was developed at the University of Verona for the production the PHA in activated sludge and the simultaneous treatment of sludge reject water. PHA has several applications in the medical, pharmaceutical and materials coatings industries, in the packaging sector and in the agricultural section. As PHA are non-toxic, water-insoluble, thermoplastic, biodegradable, biocompatible they have a high commercial value and can be used in various applications.

Introduction

The increasing demand by citizens and environmental organisations for cleaner waters led the European Commission to define water protection as one of its priorities. The Water Framework Directive (WFD) adopted in 2000 (2000/60/EC) is the legal tool for future water protection, in which the achievement of a "good status" for waters concerning both ecological and chemical quality is targeted. Additionally, the sustainable use of water resources in terms of quality and quantity is highlighted, which is related to an adequate water pricing. Wastewater Treatment Plants (WWTPs) are key stakeholders affected by these new water policies, as they are responsible for urban and industrial effluent treatment before discharge into the aquatic environment. This implies that the new challenges during the conception, design, upgrading and operation of WWTPs have to be conditioned to the current and future legal, economical and social requirements.

Since 1914, when the activated sludge process was developed, all efforts were mainly devoted to increase effluent quality. However, current aims have to be much broader, including not only those related with water and sludge quality but also considering: i) Resource recovery alternatives; ii) Energetic and Economic efficiency; iii) Impact on climate change due to the emission of Greenhouse Gases (GHG); iv) Fate of emerging contaminants and v) Odorous contamination. According to recent communications from the European Commission other issues directly related to the future of water treatment include: water scarcity and droughts (COM/2007/0414); the higher amounts and levels of wastewater treated due to the implementation of the Urban Waste Water Treatment Directive (91/271/EEC); the inclusion of priority substances as target pollutants (plant protection products, biocides, metals, Polyaromatic Hydrocarbons (PAH) and Polybrominated Biphenylethers (PBDE), pharmaceuticals and endocrine disruptors, etc.); the awareness on the contribution of sewage treatment on climate change.Water industry is especially concerned about the important energy consumption during WWT, with around 1% of the average daily electricity consumption in Western Europe due to municipal and industrial WWT.

European COST Action ES1202 "Water 2020": a novel approach for WWTPs

The conception of sustainable WWTPs needs to be based on innovative technologies developed under the following criteria: integration - including a system wide view of the plant (balance between water, sludge, energy and gases); multi-disciplinary approach- including technical, environmental, energetic, social and economical aspects and flexibility- with a WWTP adapted to the specific requirements of each country (size, location, point of discharge, etc.). This is aimed in this Action by means of an effective cooperation between experts from different fields, stakeholders and countries, participating in four different Working Groups (WGs).

WG1. Energetic self-sufficiency
Options for minimising energy consumption and optimising energy production will be investigated, aiming at converting WWTPs in net energy providers. This includes activities on energy efficient processes, such as low-temperature autotrophic nitrogen removal, anaerobic – aerobic hybrid MBRs, membrane aerated biofilm reactors, supercritical water oxidation, etc.; as well as on energy recovery alternatives, like Sewage sludge (co-)incineration or anaerobic (co-)digestion, microalgae photobioreactors integrated with anaerobic (co)digestion and bioelectrochemical systems (microbial fuel cells, hydrogen, etc.).

WG2: Resource recovery
The challenge is to conceive WWTPs not only as treatment facilities but also as producers of valuable resources by means of sustainable processes, as nutrients (e.g. ammonium nitrate from sludge, biomass digestion rejection water or urine; phosphorus as struvite; sludge composting, biochar production, etc.), bioenergy (WG1), bioplastics (e.g. production of storage polymers) and reclaimed water.

WG3: Minimising environmental and economic impacts
The economic and environmental impact of implementing innovative technologies will be assessed in terms of operational cost savings, monetary valuation of environmental benefits and LCA. Emerging contaminants, odours and GHG will be targeted pollutants included in these studies.

WG4: Process integration (DSS, control, modelling, optimisation)
WWTPs should be analyzed from an integral and multi-criteria point of view as the optimal configuration might not be the result of combining the optimum unit processes. Additionally, technological, environmental, social and economical criteria are not always convergent. The main deliverable of this WG is a DSS that incorporates those criteria in order to conceive the BATNEEC (Best Available Technology Not Entailing Excessive Costs) for each scenario.

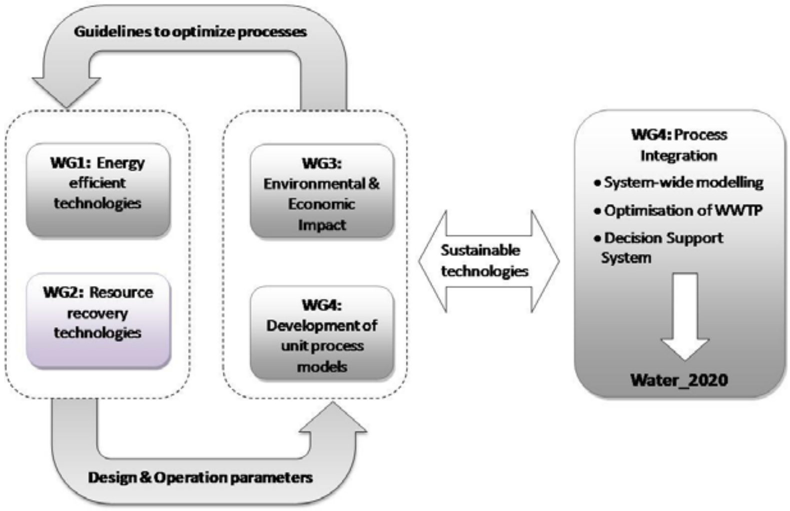

Figure 1. European COST Action ES1202 "Water2020": flow chart of WGs multidisciplinary collaboration

S.C.E.N.A.: a new treatment process for removal of nitrogen and phosphorus from high loads of anaerobic supernatant

Enhanced nutrient removal at municipal wastewater treatment plants (WWTPs) can be partly and efficiently carried out by treating the ammonium and phosphorus rich reject water produced from the dewatering of anaerobic digested sewage sludge. In conventional plants this flow constitutes 10-30% of the total nitrogen load (Gustavsson, 2010). Phosphorus concentration in reject water produced by the dewatering of anaerobically digested activated sludge, can be up to 130 mg/L (Oleszkiewicz and Barnard, 2006, Ivanov et al., 2009), while higher P concentrations may be reached when anaerobic co-digestion of sewage sludge and organic waste are applied (Malamis et al., 2014). Thus, reject water is returned to the activated sludge tank and contributes from 10 to 50% of the nutrients in the main stream of WWTPs. The via nitrite enhanced phosphorus removal associated with nitritation-denitritation (SCENA - Short-Cut Enhanced Nutrients Abatement) can realize the optimal side stream nutrients management in WWTPs. The SCENA system demonstrated its feasibility for the treatment of digester supernatant produced from the co-digestion of waste activated sludge (WAS) and the organic fraction of municipal solid waste (OFMSW), when the best available carbon source was recovered from OFMSW alkaline fermentation (Frison et al., 2013).
The R&D and optimization research Group of University of Verona and Alto Trevigiano Servizi, an Public-Owned Water Utility working in the province of Treviso in Veneto Region, realized in 2013 the pilot-scale operation of the SCENA system and is planning the forthcoming full scale development in the municipal WWTP of Carbonera (Veneto Region, Northern Italy) to realize in 2014. This study permits the integration of a conventional municipal WWTP, where the in situ best available carbon source for denitritation and via-nitrite enhanced P uptake is recovered from alkaline fermentation of sewage sludge.

Material and Methods

The SCENA pilot scheme consists of a sludge alkaline fermentation (SAF) unit coupled to a shortcut sequencing batch reactor (scSBR). The integrated SAF-scSBR has been set up within the conventional, municipal WWTP of Carbonera (Veneto, Italy). The system is applied to treat the real anaerobic supernatant for the short-cut

N removal and via nitrite enhanced P bioaccumulation. It is composed of three main units: the sewage sludge alkaline fermentation unit (reaction volume 500 L, preceded by a coarse screen to prevent retain gross material present in the primary sludge), a tubular membrane (UF) filtration skid for the solid/liquid separation of the fermentation effluent, an SBR (3 m3) for the treatment of the anaerobic supernatant to remove nutrients via nitrite pathway. The system is treating up to 6 m3/d of anaerobic supernatant that is generated from the full-scale anaerobic digester of sewage sludge in Carbonera. The main processes involved are:

- Nitritation/denitritation coupled with the best available mix of short chain fatty acids (SCFAs) to enhance the denitrifying via nitrite biological phosphorus removal (DNBPR).
- Sludge alkaline fermentation to recover the best available mix of SCFAs for P removal and/or PHA production
- Membrane filtration for the solid/liquid separation of the fermentation.

In addition, cheap and reliable system-wide process control may be realized by indirect parameters, namely: pH, conductivity, oxidation-reduction potential (ORP).

Characteristics of the supernatant and start-up

The SCENA system was inoculated with conventional activated sludge coming from the full scale municipal WWTP of Carbonera. The start-up was carried out in two stages according to Frison et al. (2013). Due to extraordinary operation of the full scale wastewater treatment plant (i.e. low temperature), low performance and transient anaerobic digestion conditions were observed during the 150 operation days (Table 1). In spite of these problematic conditions (i.e. sCOD:N ~ 2) for autotrophic growth and nitrite oxidizing bacteria (NOB) suppression in the scSBR, the complete via nitrite pathway was achieved in around 30 days.

	Days 1-60	**Days 61-150**
pH	7,5±0,1	7,3±0,2
sCOD	520±30	155±38
$N\text{-}NH_4$	270±24	439±19
$P\text{-}PO_4$	25±3	43±3
Alkalinity ($mgCaCO_3/L$)	1.065±170	1.735±100

Table 1. Characteristics of digester liquor from the Carbonera WWTP

Alkaline fermentation and impact on denitritation and DNBPR

In WWTP required to meeting increasingly stringent nutrient requirement, the pre-fermentation of primary sludge to recover SCFA for BNR systems is a almost spread alternative to purchased carbon. Acid fermentation and its dosing to the main treatment line for the conventional BNR is a known practice (WERF, 2011). The innovation of SCENA system consists of: (1) the alkaline fermentation of sewage sludge; (2) the use of wollastonite for pH buffering; (3) the addition of sewage fermentation liquid in the anoxic phase of the nitritation-denitritation for the separate via nitrite enhanced nitrogen and phosphorus removal.

During the pilot scale trials the fermentation rate was as high as 0.30±0.4 gSCVFA/gTVS, while the average composition of the fermentation liquid optimized the contents of propionate and butyrate (Table 2), so as to enhance the via nitrite phosphorus removal (Ji and Chen, 2010). Optimal fermentation HRT was in the range 5-7 days according to the content of primary and waste activated sludge, while semi-batch conditions were considered to obtain a stable production of SCFAs.

Acetate	Propionate	Butyrate	Valerate
32 %	30	21 %	17 %
sAUR	**sNUR**	**sPUR**	
mgN-NH_4oxidized /gMLVSS·h	mgN-NO_2reduced/ gMLVSS·h	mgP-PO_4bioaccumulated / gMLVSS·h	
15±2	40±10	10±3	

Table 2. Characteristics of alkaline fermentation liquid

Full scale development and economic impact

The CAPEX and OPEX conventional activated sludge (modified Ludzack-Ettinger (MLE) + chemical P removal by alum) and SCENA systems were preliminary compared for the treatment of the nutrient loadings associated with digester supernatant (Table 3).

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Costs		**M.L.E.**	**S.C.E.N.A.**
CAPEX: for MLE [a]	€/year	1.277	0
CAPEX: for SBR [a]	€/year	0	389
CAPEX: for sludge fermenter [a]	€/year	0	449
OPEX: EE for aeration [b]	€/year	72.060	54.084
OPEX: Sludge disposal [c]	€/year	13.607	7.884
OPEX: Aluminium Polychloride (PAC)[d]	€/year	10.439	0

[a] Payback time = 25 years; [b] 4 kWh/kgO_2, 0.2 €/kWh; [c] 400 €/kg$TS_{disposed}$; [d] €/tonAl 5500

Table 3 Preliminary cost comparison for management of nutrients associated with digester supernatant

Conclusions about nutrients removal

Nitritation/denitritation and via nitrite enhanced phosphorus removal from anaerobic digested supernatant were obtained in pilot scale by the in situ recovering of best available carbon source. Removal rates of 15±2 mgN-NH4oxidized/gMLVSS·h; 40±10 mgN-NO2reduced/ gMLVSS·h; 10±3 mgP-PO4bioaccumulated/ gMLVSS·h were observed and annual net income of 30-40 k€/year were estimated for a municipal WWTP with actual treatment capacity of 50 000 PE. The full scale plant is under construction and will be fully operating by the end of 2014. Future valuations will incorporate sustainability considerations (i.e. LCA, usability of the removed phosphorus).

S.C.E.N.A. and PHA production: a new treatment for bioplastics recovery from municipal WasteWater Treatment Plants

Common synthetic plastics are derived from petroleum, which is a non renewable resource. It is estimated that 4% of the global petroleum and natural gas production is used for the production of plastics and another 3-4% is consumed as energy in their production process. In 2005, 30 million tonnes of plastic waste were generated within the EU, while in the USA 31 million tonnes were generated in 2007 (US EPA, 2007; OECD Environmental Data 2008; in Morgan et al., 2010). As seen in Figure 2, only a very small fraction of plastics are actually recovered. The recycling of plastics is difficult and often problematic due to difficulties in the collection, and sorting of the different types of plastics. Also, some plastics are not recyclable and even the plastics that are recycled are of inferior quality compared to the original ones.

The plastics accumulate in the environment and cause severe environmental problems. Plastics end up in landfills occupying significant volume as their degradation is extremely slow requiring hundreds of years (>300 years). In landfills plastics occupy up to 20% of the waste volume and constitute 10% of the mass (US EPA, 2000; Dias et al., 2006). Significant proportion of plastics ends up in seas and oceans and is consumed by aquatic organisms therefore entering into the food chain. It is estimated that at a global scale approximately 1 trillion of plastic bags end up in seas and oceans.

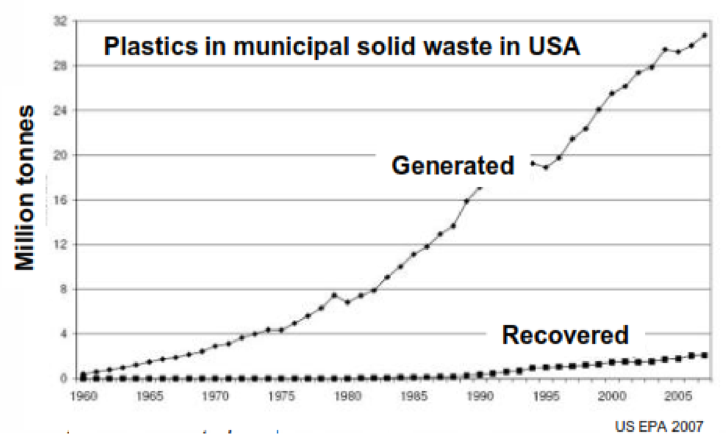

Figure 2. Produced and recovered plastic waste in the USA (US EPA, 2007 in Morgan et al., 2010)

The use of bioplastics emerges as an environmentally friendly solution that can help reduce the quantities of ordinary plastics and the resulting environmental problems. Furthermore, this will also reduce the consumption of petroleum products, the price of which has increased significantly over the last years. According to the fact sheet of European bioplastics, bioplastics are defined as the plastics which are biobased or biodegradable or both (European Bioplastics, 2014). The term biobased means that the produced bioplastic is partly or wholly derived from renewable material (biomass such as corn, cellulose, sugarcane and others). The term biodegradable means that the bioplastic can be broken down biologically by microorganisms. Nearly all conventional plastics are non biodegradable and fossil based.

Polyhydroxyalkanoates (PHA) are biodegradable and biobased polymers, well known for their application in bioplastics and are produced biologically by mixed and pure cultures. Microorganisms produce PHA as an energy and carbon reserve that can be used when food is limited (like fat is produced in humans). More than 300 different microorganisms that synthesize PHA have been isolated (Dias et al., 2006). PHA can be produced by different bacteria under external/internal growth-limiting conditions (Sudesh et al., 2000) using mixed or pure cultures. PHA are biodegradable, thermoplastic and biocompatible. Most processes for the production of PHA have been under very controlled conditions in many cases using pure cultures for the selection and accumulation of PHA, and commercial carbon sources as substrate. Currently, PHAs are produced using expensive, pre-sterilized, high-tech equipment, pure cultures and commercially available substrates. This significantly increases their production cost (Tamis et al., in press). As a result, the production cost of PHA is much higher (around ten times higher) than that of conventional plastics. The production of PHA from waste streams using mixed cultures, such as activated sludge is a promising option that can result in significant cost reduction. Wastes of different origin have been examined to assess the technical feasibility of producing PHA using waste streams. These include fermented molasses, agro-industrial waste, paper mill wastewater, chocolate waste, waste glycerol, waste frying oil, food waste, olive mill wastewater, fermented sewage sludge. Among them, the primary sludge and activated sludge can be very promising substrates after suitable treatment (i.e. fermentation) and are readily available in wastewater treatment plants (WWTPs). The integration of PHA production within a WWTP plant at full scale is of real added value. In this case, PHA is produced using the mixed culture of activated sludge and real wastewater as substrate. At the same time wastewater can be treated and the quantities of actual waste sludge can be minimized.

Material and Methods

The production of bioplastics from sewage sludge consists of the follow 4 steps :
Step 1: Production of a substrate that is rich in VFA
Step 2: Selection of PHA storing biomass
Step 3: Accumulation of PHA within biomass
Step 4: Recovery of PHA from biomass

A novel process was developed at the University of Verona for the PHA production in activated sludge and the simultaneous treatment of sludge reject water. In this process the selection of PHA storing biomass is integrated within the nitritation/denitritation process in a sequencing batch reactor (SBR) that treats the sludge reject water produced in the municipal wastewater treatment plant of Carbonera (Treviso – Italy) .The PHA production from sewage sludge is therefore an implementation of the S.C.E.N.A. process described previously.

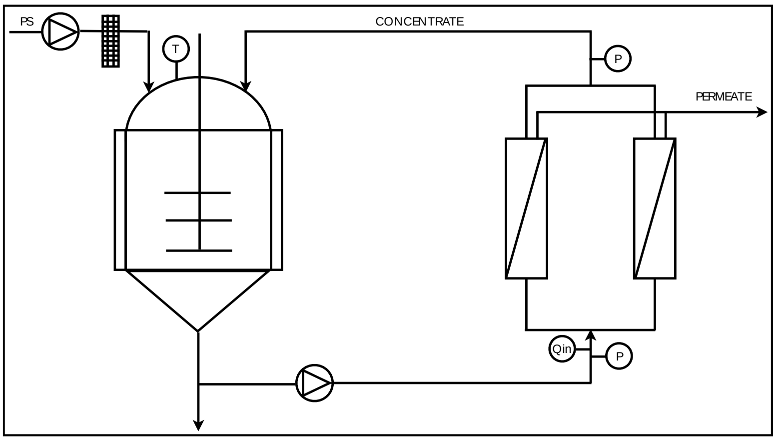

Figure 3. Flow chart showing the alkaline sludge fermentation process and the subsequent membrane separation process in the Carborera WWTP of Treviso province

Simultaneous nitritation/denitritation and selection of PHA storing biomass

In this novel process, the via nitrite nitrogen removal was integrated with the selection of PHA storing biomass. This was accomplished by adopting a feast and famine regime. The typical feast and famine regime is carried out under complete aerobic conditions. In this novel scheme the authors applied feast under aerobic conditions and famine during the anoxic conditions in order to achieve both selection of PHA storing biomass and nitrogen removal via nitrite. SBR consisted of four discrete periods: fill (12.5 min); aerobic reaction 52 min; anoxic reaction (278 min), settling (30 min) and draw (9 min). The hydraulic retention time (HRT) was kept at one day. A purge of mixed liquor was performed daily in order to keep the solids retention time (SRT) at 8 days. The feast/famine time duration was maintained at 0.2 (which corresponded to a total feast period of 52 min/cycle and a famine time period of 278 min/cycle). Specifically, under aerobic conditions the sludge fermentation liquid was supplied at a COD/N ratio of 3.0. When the SCFAs were depleted, (start of famine period) anoxic conditions were applied. During the feast conditions nitrification via-nitrite (i.e. nitritation) takes place; in the famine conditions nitrite was used as electron acceptor in order to promote the denitritation using the internally stored PHA as carbon source. Hence, the denitritation will be driven by the internal storage compounds. The above feast and famine experiments were also combined with nitrite spiking during the anoxic, famine conditions in a second experimentation. Significant nitrite depletion occurred when nitrite was spiked and in the absence of any organic carbon. This shows that the internally stored PHA is successfully used as electron donor in the denitritation process.

PHA accumulation

The last biological step is that of maximizing the PHA content within the sludge. The sludge that is rich in bacteria that are able to store PHA is collected at the end of the famine period. It is placed in a batch reactor and subjected to consecutive spiking with excess organic carbon. Two tests were set up: in the first test biomass were taken from the reactor and spiked with sodium acetate. In that case, allylthiourea was added in order to inhibit the nitrification and to evaluate the decrease of ammonia and to estimate the growth activities. In the second test biomass was collected from the reactor and was washed with a buffer solution before spiking with sodium acetate. In the latter case allylthiourea was not added, since the ammonium concentration was not significant. In the 1st case, the ammonium decrease with time was due to the growth of biomass (since nitrification was inhibited). The OUR increased gradually from 190 mgO2/Lh to 250 mgO2/L. In the 2nd experiment, after 9 hours of PHA accumulation the OUR started to decrease even when significant VFA concentration was present in the liquid phase; this shows that sludge was saturated with PHA.

Recovery of bioplastics from sludge that is ultra rich in PHA

The recovery of bioplastics from sludge that is ultra rich in PHA usually involves chemical (or thermal) treatment for the extraction, the purification and the collection of bioplastics films. The biomass is lyophilized (dried at very low temperature). Then, PHA extraction takes place with the use of chloroform (50 mL/g dry biomass) at 70oC. The extract is filtered and methanol is added to it (5 times the volume) to precipitate the bioplastics. Then the mixture is filtered and the bioplastics is captured by the filter. Chloroform is added again to the filter containing the bioplastics. The chloroform evaporates and the bioplastics are collected as a thin film from the filter.

Conclusions about PHA production

The advantages of the PHA production process developed are :

- The previously stored PHA are used as electron donor for the denitritation process without the requirement for any carbon source addition during the denitritation process
- The treatment of sludge reject water and the selection of PHA storing biomass are simultaneously accomplished. Specifically, nitrogen removal and selection of PHA storing biomass take place in the same reactor
- The short-cut via nitrite process is used to treat reject water resulting in lower aeration requirements and external carbon source requirements than conventional nitrification/denitrification.

Applications of PHA.

PHA has several applications in the medical, pharmaceutical and materials coatings industries, in the packaging sector and in the agricultural section. As PHA are non-toxic, water-insoluble, thermoplastic, biodegradable, biocompatible they have a high commercial value and can be used in various applications (Philip et al., 2007). The copolymer of 3-hydroxybutyrate and 3- hydroxyvalerate, P(3HB-3HV), has a high potential to substitute conventional plastics since it has thermoplastic properties comparable to those of petroleum-based polyolefins such as polypropylene and polyethylene (Lee, 1996). Potential applications include sutures, patches, stents, tissue regeneration scaffolds, nerve guides, grafts, implants, wound dressings, and other medical products. Hence, the potential application of PHA as replacement for petrochemical based polymers is gaining popularity. These desirable properties in compounding and blending have broadened their performances as potential end-use applications.
A high level of biocompatibility is usually needed before foreign materials can be incorporated into human body. Shape, surface porosity, chemistry of the materials and the tissue environment play important roles in biocompatibility. PHA has a distinct advantage in the medical field over silicone, a traditionally used polymer, which is believed to have maligned effects and contribute to cancer cell growth. Although PHA can serve as substitute biomaterials for silicone, five key elements need to be fulfilled for successful application of PHA in tissue engineering, i.e. biocompatible, support cell growth and cell adhesion, guide and organize the cells, allow in growth of cells and allow passage of nutrients as well as waste products, and finally biodegradable without producing any harmful compounds. Biomaterials such as P(3HB) and P(3HB-co-3HHx) were among the most extensively studied PHA used in the applications of tissue engineering and controlled drug-released (Philip et al., 2007).

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