APPLICATION OF THE BIOTECHNOLOGICAL POTENTIAL FOR ENVIRONMENTAL CHALLENGES IN THE CHEMICAL INDUSTRY

The biotechnological potential is ecoefficient and thus will become increasingly applied in future

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Abstract

Nature has an enormous potential to cycle materials and energy. This potential, and specifically that of biological processes can be applied in the chemical industry to recycle or treat waste, wastewater, and off-gas, and thus reintegrate the man-made, synthetic chemicals into the natural cycles.

This contribution describes some powerful and innovative biotechnical processes investigated in and partly applied at Ciba Specialty Chemicals Inc., Switzerland for the breakdown of C-, Cl-, N-, S-, and P-containing molecules for water, air and soil treatment. Among these are laboratory investigations on the degradation of atrazine or chlorophenols in soils, the large-scale application of microorganisms capable of mineralising aromatic or chlorinated aliphatic compounds in fixed-film bioreactors for groundwater treatment, the anaerobic treatment of chemical effluents, or the removal of solvents from off-gas using biological trickling filters.

Although the biotechnological potential available is vast, its applicability in the environmental field is slow. Possible reasons and potential barriers to overcome are discussed from a perspective of the chemical industry. Chances for optimal solutions including biological processes increase if the approach to solve environmental challenges is holistic, if the wastewater or off-gas is well characterised, if cheap and reliable biodegradation tests are used coupled with professional interpretation of the test results, and if interdisciplinary know-how transfer occurs.

1. Introduction

Excellent solutions in the environmental field are those which avoid problems from the start. Therefore, if the principle to avoid, reduce and dispose of the wastes end of the process is strictly followed, very few environmental problems would occur, and thus not many environmental engineers and biotechnologists would be required. In reality, we are far from such an ideal situation. In fact, applying too strict a principle would make neither economical nor ecological sense in many situations. Example: it will mostly be better to collect small effluents and treat them together in a cheap and environmentally friendly way than to treat them individually, or to incinerate the wastewater with the result of a "zero-discharge facility", which is "zero discharge" in relation to wastewater but not to energy or air. Therefore, in practice, rather the optimal than the maximal solutions are looked for. Biotechnological solutions are especially advantageous in the long run, they generally require more volume (higher investment cost) than chemical and physical options, but they are often far more advantageous regarding resources including energy requirements and operation costs.

In the following chapter, case studies are presented of biological processes investigated and implemented in the chemical industry to solve environmental challenges. Some of them have been transferred to full scale, while others still wait to be applied some day. Very often, the biological process used was just one of a chain of process steps to reach required goals.

2. Biotechnological processes to remove/degrade chemicals

During the last 15 years, many biological processes were studied and partially applied at Ciba Specialty Chemicals, Switzerland, to eliminate waste chemicals (Table 1).

2.1 REMOVAL OF ORGANIC CARBON

In contrast to the food industry, where high loads and concentrations of a more or less constant composition of organic materials are converted by applying anaerobic processes, larger quantities of carbonaceous compounds are most often distilled, recycled or used as fuel replacement in the chemical industry. Cases with high volumes and loads of organic materials to be degraded are rare, and are restricted to wastewaters containing waste carbohydrates or organic acids. Such type of wastewater was generated in a dyestuff factory. The large amounts of dilute aqueous acetic acid and ethylene glycol among trace amounts of aromatic chemicals could neither be avoided nor replaced nor recovered economically and thus was pre-treated anaerobically in a 170 m^3 reactor. For the successful application, it was important to identify toxic substances inhibiting the anaerobic microorganisms. The major "toxic chemical" was sulphuric acid which was replaced by an alternative inorganic acid to avoid inhibition due to H_2S formation.

Table 1. Environmental biotechnological processes tested and applied at Ciba Specialty ***Chemicals*** *Inc. during the last 10 years*

Element	Examples studied	phase of application (1999)
C	Removal of high organic loads and colour from wastewater (acetic acid, diethylene glycol, dyestuffs) by an anaerobic end of process treatment	Cheap, anaerobic pre-treatment processes (up-flow-anaerobic sludge blanket process) successfully in operation since several years
Cl	Removal of chlorinated chemicals determined as AOX (adsorbable organic halogens)	Several successful full scale end-of-pipe process applications in operation using a combination of fixed-film bioreactors and activated carbon adsorbers
Cl	Degradation of low concentrations of chlorinated hydrocarbons (chlorinated aromatic compounds, 1,2-dichloroethane [DCA], tetrachloroethene [PER]) in groundwater	Aerobic full scale process to remove DCA using laboratory strains; an anaerobic-aerobic full scale process followed by activated carbon adsorption to remove PER, pilot studies eliminate aerobically chlorinated aromatic compounds at low temperatures, low concentrations, and high hydraulic loading rates
Cl	Degradation of chlorinated phenols or dichloromethane in industrial waters	Laboratory and pilot studies, potential not yet applied
Cl	Removal of chlorinated pesticides from soil (e.g. atrazine) and wastewater (substituted phenols)	Laboratory, bench, and field scale trials using aerobic microorganisms with special degradation capabilities, concept developed to remediate a contaminated site including *in-situ* remediation and soil washing
Cl	Removal of chlorinated solvents from off-gas	Pilot studies using aerobic microorganisms to remove chloromethane, 2-chloropropane, DCA and other synthetic compounds
N	Nitrification and denitrification of ammonia and nitrate, respectively	Classical processes implemented at several production sites
N	*s*-Triazine herbicides (atrazine, simazine, etc.) removed from process streams as N- sources	Laboratory approach worked; field trials failed due to the presence of nitrogen fixing bacteria competing for C
S	Biological recycling of dilute waste sulphuric acid using an anaerobic process	Excellent laboratory performance, process not followed up further due to unfavourable economics
S	Hydrogen sulphide (H_2S) and mercaptan removal from process air	Excellent performance in laboratory and pilot scale, first biological trickling filters under construction (20 m^3 working volume)
P	Biological P fixation	Either no P available or too high P loads are discharged, the bio-P process is applicable as "polishing treatment" only (in the chemical industry)
P	Phosphonates as P- sources	Degradation potential applicable at P limiting conditions
P	Organic phosphates as C- and energy sources	Conventional biological elimination possible

Wastewater containing high quantities of sulphuric acid were excluded from the anaerobic treatment. Methanol as emergency feed stock helped to run the anaerobic process reliably, because it guaranteed a continuous methane production rate, which allowed some permanent removal of toxic H_2S by stripping. The biological process was much cheaper than the previously applied chemical wastewater treatment. In addition to the carbon load, the colour was removed very efficiently by this process.

Another application of the anaerobic potential was the pre-treatment of a highly concentrated leachate of an old dumping site. The H_2S produced from the trace sulphates precipitated the heavy metals efficiently [1].

2.2 CHLORINATED COMPOUNDS

In industrial wastewaters, chlorinated compounds are either analysed as individual substances (e.g. pesticides like atrazine) or as sum of halogenated chemicals (AOX), which adsorb onto activated carbon. We applied microorganisms mineralising chlorinated chemicals at full scales (10, 30 and 500 m^3 aerobic reactors) using the following concept: The chemical wastewater is treated in a series of fixed-film bioreactors followed by activated carbon adsorption. Slowly growing bacteria, known to have a broad degradation potential developed preferably in the last reactor. With the broader degradation potential available, more chlorinated chemicals were mineralised and thus more compounds contributing to AOX were biologically eliminated. As a consequence, less AOX had to be removed by adsorption, which resulted in a longer service life of the activated carbon columns and thus in lower operation costs.

The aerobic degradation of chlorinated compounds serving as C- and energy source such as atrazine [2] or dichloromethane [3] has been investigated at laboratory and pilot scale. Although the chemicals were efficiently removed, the biological processes were not applied at full scale due to different reasons such as economical considerations, production stops, alternative chemical or physical environmental processes.

Low concentrations of chlorinated hydrocarbons in groundwater and leachate of solid waste disposal sites were successfully treated at laboratory and pilot scales, using the site specific microbial degradation potential, enrichment cultures, or pure cultures isolated and grown under laboratory conditions. Crucial for the successful transfer of the biotechnological know-how was not only the microbiological knowledge but also the engineering competence in reactor technology. Intensive pilot studies revealed that low contaminated groundwater can be treated aerobically at similar organic loading rates as domestic or industrial wastewater treatment plants, even though the feed and effluent concentrations are up to 100 times lower than those of industrial wastewater treatment plants ([3, 4], Table 2). In contrast to the typical industrial or domestic wastewater treatment, the hydraulic residence time for the groundwater treatment was as low as 15 to 20 min, since all the pollutants were dissolved and thus were rapidly taken up by the bacteria (Table 2). At higher hydraulic rates or shorter residence times, the conversion possibly became diffusion limited. The removal of DCA from groundwater at full scale was described in detail [5].

Tab. 2. Comparison of the hydraulic retention time, the organic loading rate, and the elimination efficiencies in different water treatment systems

Parameter	Units	Domestic wastewater	Chemical wastewater	Groundwater
Feed concentration (as organic compound)	mg/L	10 - 100	100 - 1000	1 - 10 (3)
Effluent concentration	mg/L	< 10	50	< 10 μg/L
Hydraulic retention time	H	2	12	0.3
Specific hydraulic loading rate (1)	$M^3/(m^3 \cdot d)$	12	2	72
Temperature	°C	10 - 35	10 - 40	8 - 15
Organic loading rate (2)	$Kg/(m^3 \cdot d)$	0.06 - 0.6	0.2 - 2.0	0.07 -0.7
Sludge concentration	g SS/L	2	6	20 (4)
Sludge loading rate	g organics/ (g SS·d)	0.03 - 0.3	0.03 - 0.33	0.004 - 0.035 (5)
Elimination efficiency	%	80 - 90 (6)	ca. 90 (6)	99 - 99.9 (7)

(1) related to the empty bed volume; (2) related to the amount of pollutant per unit reactor volume; (3) chlorinated aromatic and aliphatic compounds (4) estimate for fixed film reactor; (5) a considerable part of the sludge is mineralised under these conditions; (6) based on dissolved organic carbon, (7) based on single compound analysis

The presence of bacteria supplied with fertiliser and H_2O_2 allow the reduction of the synthetic chemical from the mg/l-level to levels below 10 μg/L at temperatures of 8 to 12 °C and at hydraulic residence times below 1 h. As a result of the innovative biotechnical approach, the operation costs fell seven fold compared to conventional treatment options.

Factors limiting the application window of biological processes were also investigated in soils, because many excellent *in-situ* applications to decontaminate gasoline contaminated land demonstrate the powerful biotechnological potential. An example of the full scale application of chlorophenol contaminated soil in biopiles has been described by Häggblom and Valo [6]. Our initial soil studies ware carried out using atrazine as model compound. This chemical showed only weak adsorption properties in soils with a moderate amount of organic matter, thus atrazine was fully available for biodegradation. In addition, the soil required to be inoculated by special microorganisms to achieve atrazine mineralisation. In bench scale trials, a low number of bacteria (0.1 mg/kg soil) able to mineralise atrazine removed this chemical so rapidly from soil that its herbicidal activity against atrazine-sensitive plants was lost [7, 8]. Thus the kinetics of the atrazine activity versus degradation will finally determine certain fields of application of the atrazine degrading organisms.

Another model compound used for our studies was 2,6-dichlorophenol (DCP), which was one of the major pollutants of a former disposal site. A pure microbial culture was found and isolated from soil and water samples from that site [9]. One of the remediation concepts developed included *i*) the incineration of the highly contaminated soils, *ii*) an alkaline soil washing treatment for the moderately contaminated soils up to 1 g substance/kg soil with a subsequent biological treatment of the washing medium in a fixed-film bioreactor, and *iii*) an *in-situ* biological polishing treatment for concentrations below 100 mg/kg soil [15]. The aqueous extraction solution of the moderately contaminated soil contained 1 g/l DCP. This solution was efficiently purified in a fixed-film aerobic bioreactor to levels below the detection limit of DCP (0.3 mg/l) and what made it possible to recycle the extraction liquid [10]. Although the environmentally more friendly concept that included soil washing and biological treatment of the extraction liquid for the moderately contaminated soil looked promising, it did not compete successfully with the conventional alternatives: a thermal desorption process followed by a thermal treatment of the off-gas was finally chosen to clean up the soils.

Off-gas treatment has a large potential for industrial applications. So far, compost filters have been widely applied to treat odorous gases. In the chemical industry, these filters could rarely be applied, because many compounds yield acid degradation products. As a result of the biological breakdown, the pH in the compost filters fell and the air cleaning efficiency decreased. A very promising tool is the biotrickling filter, in which bacteria fixed on an inert surface clean the air by mineralising the organic off-gas components. Chemical and physical processes limiting the biological turnover are a technical challenge to overcome to make the biological process competitive and reliably applicable. In the trickling filter, metabolites such as inorganic acids can be easily washed off by the aqueous recycle stream. Pilot studies showed that chlorobenzene together with dioxane and toluene were eliminated at rates between 20 and 100 g $C_{org}/(m^3_{reactor\ volume} \cdot h)$. Similar removal rates were obtained for 1,2-dichloroethane (DCA) using a 1 m^3 pilot reactor. The temporal variation in load and concentration of the chemicals and the absence of oxygen require process modifications (humidifiers, buffers such as activated carbon adsorbers, peroxide feeding options). At the present stage of process development, the technology is often not cheap enough to compete with chemical and physical alternatives. Therefore, the field of application is still small. Nevertheless, we investigated the use of this technology for the removal of methyl chloride, DCA, different acrylic esters, 2-chloropropane, and aliphatic amines. So far, a 20 m^3 trickling filter prototype has been taken into operation in 1999. It is treating off-gas which was incinerated before and which contains amines, isopropanol and traces of 2-chloropropane. A second biological trickling filter is under evaluation for the removal of 3 kg/h DCA. In an adjacent chemical company in Pratteln, Switzerland, a 350 m^3 trickling filter has recently been erected to remove chlorinated benzenes and toluene.

2.3 NITROGENEOUS COMPOUNDS

Bulk amounts of most nitrogen-containing compounds are generally recycled or disposed off by other than biological unit operations. In the normal case, only low amounts and low concentrations of N-containing compounds are discharged into effluent treatment plants. These chemicals serve as N-source for the bacteria, mineralising the carbonaceous chemicals. Examples for compounds discharged in larger amounts as chemical effluent are waste ammonia, nitrates, solvents difficult to recycle such as dimethylformamide, or secondary and tertiary amines. The many new regulations issued during the last 10 years required the modification of numerous conventional wastewater treatment plants into nitrifying and denitrifying treatment plants.

Nitrifying conditions in industrial wastewater are obtained in treatment plants where a high sludge age prevails. These conditions, however, also allow the development of slowly growing microorganisms known to have a broader degradation potential than the fast growing strains. As a result, difficult to degrade compounds are often co-oxidised in nitrifying plants, whereas they seem to be refractory in conventionally operated plants. An example is the disappearance of *cis*-1,2-dichloroethene (unpublished) in a two stage fixed-film nitrifying bioreactor converting 300 mg/l ammonia to nitrate [11].

Nitrate as a waste product in chemical effluents can hardly be recycled economically. A very efficient disposal technology is the denitrification process. If used in an industrial wastewater treatment plant, nitrate replaces oxygen, and thus may lead to considerable savings in (aeration) energy. This potential will be applied soon in one of our pigment plants, where tons of waste nitrate have to be disposed off, daily. The site itself does not discharge carbon compounds, which could have served as electron donors. Therefore, waste nitrate will be transported via pipeline to the effluent treatment plant of an adjacent paper works to replace pure oxygen used to increase the aeration capacity and part of the blower capacity.

Certain pesticides were tried to be mineralised as nitrogen source using the biological potential of strong oxidising enzymes produced by the microbial cell under N- (or P- or S-) limiting conditions. Unfortunately, N-limiting conditions in the chemical industry are exceptional, and the biological processes are difficult to run reliably due to the competition of N-fixing bacteria competing for the carbon compounds available. As a result, the window of application of this degradation potential is considered very small.

2.4 SULPHUROUS COMPOUNDS

One of the bulk sulphur compounds used in the chemical industry is sulphuric acid. Whereas economic high temperature processes exist to recycle concentrated waste acid, no solution other than neutralisation or precipitation and disposal as waste gypsum exists for the dilute acids below 15 to 20 % H_2SO_4. For this purpose, a few years ago, we combined a biotechnological with a chemical process to recycle sulphuric acid via H_2S and elemental sulphur. The biological process was run anaerobically using acetic acid, another abundant waste in the chemical industry, as reductant. Both, sulphuric (H_2SO_4) and acetic (CH_3COOH) acid were converted to the two weaker corresponding acids H_2S and H_2CO_3 with the biological process run at neutral conditions [12]. So far, the process was never applied at full scale due to the cheap price for sulphur and the still abundant sites for gypsum disposal.

Mercaptans and H_2S are often the source of odor problems. They were usually oxidised in scrubbers using strong oxidising chemicals. In future, off-gases containing pollutants such as sulphur containing compounds as well as smelly chlorinated or N-containing volatile chemicals will be decomposed more and more in low-energy consuming systems such as compost filters and biotrickling filters. Especially the latter allow to control the biological activity much better than the simple compost filter, which is prone to clogging, acidification and drying out.

2.5 PHOSPHOROUS COMPOUNDS

Whereas numerous domestic wastewater treatment plants have been converted/erected/modified to remove phosphates using the biological potential of microorganisms to fix and release increased amounts of inorganic phosphate at different redox conditions, the chemical wastewater treatment plants are unlikely to undergo such modifications. The main reasons are that substrate concentrations determined as total organic carbon (TOC) or biological oxygen demand (BOD) are so high, that phosphate often must be added to support the unlimited growth of activated sludge. To remove high phosphate quantities, the chemical precipitation of concentrated P-containing effluents at the source of the pollution is usually much more efficient than a bio-P-treatment process at the end of the pipe, where only traces (a few mg/l) of P are eliminated.

The removal of phosphonates under laboratory conditions has been studied intensively. This class of substances can certainly be degraded under P-limiting conditions. The removal of phosphonates in presence of inorganic phosphates has been reported [13] but could not be obtained in pilot scale studies (Stucki, unpublished). The biological elimination of phosphonates is assumed to proceed at one of Ciba’s effluent treatment plants in Switzerland where low amounts of phosphates are available and considerable quantities of phosphonates “disappear”. In contrast to phosphonates, organic phosphates are easy to degrade aerobically. The resulting phosphate has to be precipitated subsequently.

3. Technical barriers delaying the application of environmental biotechnological processes in the chemical industry

Although the biotechnological potential to solve environmental challenges is huge, its applicability in the chemical industry is slow. Barriers preventing any new technology to be applied exist on different levels, e.g. at the level of regulation and legislation, at the economic level, and last but not least on the technical level. In this chapter, some technical barriers are identified and strategies to overcome these hurdles are suggested (Table 3).

A technical barrier to apply innovative biological solutions often exists already in the approach to solve an environmental challenge. Many engineers and chemists responsible for the management and realisation of environmental projects in the chemical industry are obviously more familiar with chemical and physical processes, which seem to be more predictable. There is a lack of know-how to estimate the biological degradation potential and how to improve the reliability of the biological processes.

Until today, environmental processes are often implemented without a holistic perspective of the problem, and usually under a big time pressure. As a result, many environmental activities are, if strictly analysed, counter-productive, thus polluting the environment more than if nothing was done. Examples are the moving of contaminated soils from one site to a distant site for disposal, the use of a high-energy technology for the removal of trace amounts of biodegradable chemicals, or the stripping of water contaminants to the atmosphere. The most important chance for biotechnological processes is if ecoefficient processes were preferred to solve environmental problems. Ecoefficient processes might be defined as those showing the highest environmental gain at the lowest costs. We have used several modified methods originally developed for life cycle analysis to compare and assess environmental processes. We realised that biological processes correctly applied often outperform chemical and physical alternatives, which require more energy than the biological options. Nature continuously optimises energy consumption of its processes. Natural processes are very energy efficient, and thus, the applicability of biological processes is very promising if ecoefficient options are favoured.

The biodegradative potential to treat water, air and/or soil is still underestimated in the chemical industry. The most widely used rule of thumb to estimate the extent of biodegradation of a certain wastewater is by the ratio of the chemical oxygen demand and the biological oxygen demand within 5 days: COD/BOD_5 ratio. Whereas this term is successfully applicable in the field of domestic wastewater treatment, the chemical environment may influence both parameters COD and BOD too much, and thus the ratio is very unreliable. Compounds at a high oxidation level like glyoxylate yield very low COD/BOD_5 ratios and thus pessimistic degradation forecasts even though they are excellently biodegradable. Chemicals such as H_2S, hydrazine, chloride ions in the g/l-range, SO_2 or NO_2 have a big impact on the COD/BOD_5 ratios, and thus lead to false negative conclusions. The evaluation of biodegradability of certain wastewaters or chemicals based on the extent of TOC elimination is considered as more reliable, and is used at most sites of the Ciba Corporation for the internal wastewater management.

Table 3. Technical barriers delaying the application of biotechnological solutions to solve environmental challenges in the chemical industry

Challenge	In the past	In future
Ecoefficiency	An holistic perspective frequently missing, problems shifted from water to off-gas, or from off-gas to water, etc.	Optimal environmental processes in relation to economics and ecology are looked for - a big chance for biotechnological processes
Indicator for biodegradability	COD/BOD_5 ratio	DOC (dissolved organic carbon) biodegradation
Testing time to determine the biodegradation potential in a given wastewater treatment plant	New tests requiring shorter testing times are developed and used	Cheap test set-up, low maintenance work, long incubation times (14 days and more)
Microbial growth rate	Fast growing strains are considered as those with the better application potential	Slowly growing bacteria are equally applicable but require sophisticated engineering, good reactor design, etc.
New degradation abilities	Isolation of new strains	Application of sludge with special degradation competence to evaluate the extent of degradation and/or speed up initial degradation rates
Off-gas treatment	Quite expensive energy- intensive technologies are implemented to remove biologically degradable chemicals	Field of application will be widened, biotrickling filters will clean highly and weakly contaminated off-gases, a requirement for success is an interdisciplinary engineering approach

Many new tests to determine the extent of biodegradation in shorter time periods are developed. Often, the newly designed tests are used to determine the degradation potential of certain compounds in wastewater treatment plants. Again, the application in the domestic field is acknowledged due to the more or less constant wastewater composition. However, the biodegradation potential in the chemical industry based on batch processes is likely to be underestimated with these short-time tests, since chemicals whose degradation requires time for adaptation, induction of certain catabolic enzymes, or growth of slowly growing microorganisms until degradation is detectable will show negative results. Therefore, too short biodegradation tests are likely to yield too low degradability predictions. At many sites of our corporation, tests to determine the inherent biodegradability within 2 to 4 weeks are carried out. A simple test set-up consisting of a laboratory shaker and some Erlenmeyer flasks allows to run many tests cheaply. The extent of biological elimination is determined on the basis of DOC. Analysis is done at the test start and after each week.

Microbiologists mostly favour fast growing bacteria and ascribe to these organisms a higher application potential. Whereas this might be true for production processes, the growth rate in environmental biotechnology is often of secondary importance. Even slow growing strains such as e.g. the acetotrophic methanogens contribute to powerful and extremely efficient biological processes, provided that the reactors are designed such that the bacteria are kept in the system where they can bring about their degradation potential.

New bacteria or sludge capable of degrading chemicals known as non-biodegradable are detected every year [9, 14]. In many cases, not enough attention is paid to the fact, that the degradation potential of sludge is usually restricted to a certain site, an off-gas filter, or a specific wastewater treatment plant receiving the substances under consideration for a long period of time. In a few cases, we have detected that the purification efficiency of wastewater of a certain production process decreased considerable when the production was moved from one site to another. Thus, the competence to degrade certain chemicals was lost and had to be recovered at the new site. We consider the use of sludge able to eliminate the substances under consideration as crucial to estimate the extent of biodegradation at the start of a project, simply to keep the biological option viable. Later, the transfer of sludge with special degradation capabilities form one site to another might speed up the degradation competence of a given environmental system such as wastewater treatment plants, off-gas filters or remediation sites.

In the chemical industry, low loads of odorous compounds are often cleaned using huge amounts of energy and expensive equipment. Although different systems to treat off-gas biologically are on the market, their application in the chemical industry is small. Process limitations are not primarily seen in the biological field, but also regarding chemical (mass transfer), physical (humidity) and engineering (nozzles) issues. The field of application will be widened with the trickling filter, where low volumes/high concentrations and high volumes/low concentrations will be economically treatable. Success in the field of biological off-gas treatment requires an interdisciplinary approach.

4. Conclusions

Biotechnological processes offer ecoefficient solutions for environmental challenges in the chemical industry. Case studies performed during the last twelve years at Ciba Specialty Chemicals, where this potential was tried to be applied wherever possible show that the field of application becomes wider. To apply biological processes more frequently, a holistic approach to solve the environmental issues is required. In addition, simple, cheap, and reliable evaluation methods to determine the extent of biological elimination and degradation of chemicals in given treatment facilities should be applied.

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