Chapter 9
Spinoffs of Phyoremediation and/or Microorganism Consortium in Soil, Sediment, and Water Treatments and Improvement: Study of Specific Cases and Its Socioeconomic and Environmental Advantages

Hayfa Rajhi and Anouar Bardi

Abstract A large amont of rejected materials and their pollution can create multiple challenges in terms of sustainable development, law, and the environment. Faced with this problem, it is necessary to study and develop methods that make it possible to extract or stabilize pollutants in the biotope matrix (sediment, soils, and water) before storage and possible recovery operations. Different cases were presented, namely, (I)a bioremediation of urban wastewater by microalgae (phytoremedaition), (II) bioremediation of industrial wastewater using anaerobic digestion (using anaerobic microorganisms) and solid fermentation (using fungi), (III) bioremdiation of sediment and sludge using anaerobic consortia (remediation associated with bioenergy production), and (IV) bioremediation using biosurfactant microorganisms' activity. In addition, the effect of an economic and environmental bioremediation study was carefully discussed in this chapter. In fact, the use of bioremediation process is in perfect harmony with recent sustainable environmental development.

Keywords Bioremediation · Phytoremediation · Waste treatment · Consortia · Bioenergy · Sustainable development · Economic growth

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9.1 Introduction

Applied Environmental Microbiology Section encompasses two main areas of research in environmental microbiology. The first area concerns the study of microorganisms found in soils, sediments, water, and air, in addition to their relationships with each other and with animals, humans, and plants. The second field of environmental microbiology is that of the study of microorganisms involved in biotechnologies that affect all aspects of human activity, such as food sciences, agriculture, biomass valuation, techniques, depollution, bioremediation and pharmacology, etc. In this context, we can suggest that the bioremediation research was basically based to microorganism's pathways as well as their different environment response behaviors (Rajhi 2012).

Biological methods rely on the metabolism and activity of communities of bacteria, fungi, higher plants to remove, degrade, or stabilize pollutants. We distinguish two main processes: phytoremediation and bioremediation. Phytoremediation is a biological process basically used by plants to treat soil and/or water. In addition, plants have the capacity to extract, accumulate or degrade polluted efficiently. The plant phytoremediation consist to the interaction of roots and microorganisms associated. This bioprocess allows soil and water decontamination from higher organic and mineral-polluted compounds. Phytodepollution technique is a pollution control technology that appears to be effective against a broad spectrum of organic and inorganic pollutants. It can be used on solid (polluted soil), liquid (contaminated water), or gaseous (filtration of air laden with harmful volatile compounds) substrates. Main phytodepollution mechanisms are phytoextraction, phytodegradation, rhizodegradation, and phytostabilization (Perchet 2008).

In Bioremediation process, the microbial strains (bacteria and /or fungi) were invested to degarde the wastes. The bioremediation is bioprocess that has a huge applications, including cleaning soil water, soil, industrial sludge. There are microorganisms capable of efficiently degrading pollutants such as petroleum products, oils and greases, and hydrocarbons. In addition to eliminating compounds that have harmful effects on the environment, this technique makes it possible to reduce sanitation costs. Microorganisms need nutrients and a carbon source to provide the energy necessary for their growth and survival. Bioremediation is multidisciplinary, thus taking into account microbiology, engineering, ecology, ecotoxicology, soil science, and chemistry. Several methods use microorganisms as the main actor in bioremediation (Perchet 2008). Like other treatments, bioremediation processes can be grouped into two sub-parts: the first devoted to "in situ" depollution treatments and the second to "off-site" treatments. In situ treatments are required in cases where pollutants have penetrated deep into the soil and are distributed over large areas, making excavation too expensive. These treatments aim to activate biodegradation processes and improve the accessibility of microorganisms to oxygen (Perchet 2008). Biological treatment by soil aeration (or bioventing) is a promising technology which consists of stimulating the in situ biodegradation of pollutants in the soil by supplying the microflora in place with the necessary oxygen. Oxygen is provided by injecting air into the contaminated area. For this method to be effective, it is necessary for the porous medium to have a good content of mineral elements and a soil colonized by microorganisms suitable for pollution, so that bioventing technique can be envisaged. Regarding the treatment of soils by injection of hydrogen peroxide (H_2O_2), some bacteria can use H_2O_2 as an oxygen source up to concentrations of 1 g/L, which represents O_2 contents 50 times higher than those measured in water saturated with the air. Thus, the use of H2O2 was considered for the treatment of polluted areas. This treatment can only be advantageous if the contaminated soil is sufficiently permeable to allow effective percolation. The addition of hydrogen peroxide can lead to precipitation of iron, which can lead to clogging of soils. It is important to control the decomposition of hydrogen peroxide. Indeed, too rapid decomposition runs the risk of over-saturating the water with O_2 which will tend to degas and block the circulation of fluids. Too slow decomposition reduces microbial metabolism and the speed of decontamination. Treatment of soils associated with that of the water ground, this type of treatment results in pumping water from the water ground, which is surface treated (filtration, stripping, and biological treatment), often re-aerated, supplemented with mineral nutrients sometimes with microorganisms before being reinjected into the soil. Injection of microorganisms may be necessary in the case of specific pollutants having a microorganism suitable for degradation. However, the use of this technique is limited and cannot be used in case of contaminated deeply soil. Most of the time, using these off-site processes reduces processing times. (I) The aim of reactor or bioslurry treatments, is to mix microorganisms and pollutants in order to facilitate their degradation. For bioreactors in anaerobic condition, the final objective is to mineralize the pollutant or to reduce its bioavailability or that of metabolites by binding them irreversibly to the matrix. (II) Composting process, the soil is mixed with agricultural by-products (alfalfa straw, sugar beet stalks, and vegetable waste). (III) The treatment in biotertre (or biopile) consists in stimulating or optimizing the metabolism of microorganisms to break down soil pollutants. This technique is carried out under cover, with treatment of gases and juices produced (leachate), aeration, humidification, and addition of nutrients (nitrogen and phosphorus) to the substrate to be decontaminated (Perchet 2008). (IV) Controlled spreading (or landfarming) or controlled landfarming was for a long time the only biodegradation process used (on a small scale) for polluted materials with little hydrocarbon content. It requires large areas with a spreading plan that is difficult to put into action (many players to be convinced and controls to be carried out). (V) Laggooning used for the treatment of wastewater or mine water, lagooning technique consists in developing, downstream of zones generating these pollution, areas through which the effluents flow. This technique is a purification process which consists in maintaining the wastewater in shallow ponds for a long period during which the action of microorganisms, plants, wind, and sun, with or without artificial aeration, causes the slow degradation of organic matter. (Rajhi et al. 2018, 2020).

In this chapter, a summary of results of the research work carried out was presented. Different cases were presented, namely, (I) a bioremediation of urban wastewater by microalgae (phytoremedaition), (II) bioremediation of industrial wastewater using anaerobic digestion (using anaerobic microorganisms) and solid fermentation (using fungi), (III) bioremdiation of sediment and sludge using anaerobic consortia (remediation associated with bioenergy production), and (IV) bioremediation using biosurfactant microorganisms activity. In addition, an economic and environmental bioremediation study effect was carefully discussed.

9.2 Phytoremediation

9.2.1 Definition of Phytoremediation

Phytoremediation is a bioprocess that uses the metabolism of plants and (algae/microalgae) to transform, to degrade, to concentrate, and to stabilize or to volatilize pollutants (organic and inorganic molecules, metals, and radioelements) contained in contaminated soil/sediment or water. More precisely, it is a set of in situ techniques (which can be installed directly on the contaminated site) relying on plants to extract, degrade, or immobilize contaminants from soils, sediments, sludge, water from surface or underground, and in the air.

Phytoremediation is an efficient economic bioremediation strategy based on solar energy conversion.

9.2.2 The Different Phytoremediation Processes (by Plants)

Different phytoremediation processes were based on the following different processes such as extraction, stabilization, degradation, and volatilization.

9.2.2.1 Phytoextraction

In this bioprocess, plants can remove contaminants, such as trace metal and metalloid compounds, as well as different organic contaminants, from the soil and accumulate them in their aerial parts which can then be harvested. This is the most used method. Plants can acidify the rhizosphere or even secrete ligands capable of chelating metal ions. Sometimes, mycorrhizal fungi form symbiosis with plant roots and aid in uptake of metals when soil concentrations are low, and conversely, can help plants resist phytotoxic levels (Peer et al. 2005).

9.2.2.2 Phytostabilization

Plants reduce the bioavailability of soil–rhizosphere contaminants by chemical immobilization, such as precipitation, stabilization, absorption as well as a prevention of lateral depth movements via erosion/and leaching. Plant stabilization can prevent the dispersion of contaminants in surface and groundwater. A vegetated land cover minimizes wind and water erosion. In addition, this technique can prevent the animal against direct with pollutants. Plants can minimize the formation of contaminated leachate and limit the migration of dissolved contaminants into groundwater. In contrast, a risk of pollutants conversion into less bioavailable forms can be occurred when these precipitate in the rhizosphere (Giasson et al. 2005).

9.2.2.3 Phytodegradation

Plants absorb and break down organic pollutants in their tissues, as well as can secrete an enzyme of degradation in the rhizosphere. Decontamination is carried out in the rhizosphere by microorganisms, which growth and activity were stimulated by plants. The degradation of organic compounds can be complete (generating inorganic elements such as CO_2 and H_2O/Cl_2), but it can also be incomplete, leading to the stable intermediates' formation (called metabolites), which can be stored in the plant. This type of remediation can be used, among other things, to remedy contamination problems with petroleum hydrocarbons (Pilon-Smits 2005).

9.2.2.4 Phytovolatilization

Organic and inorganic compounds are extracted from the soil by plants, transported in their vascular system, and then exposed to the atmosphere through transpiration, which can be completely volatilized, and therefore, it is not necessary to harvest and treat used plants (Olson et al. 2004). However, the risk of pollutants air transfer into atmosphere must be examined before the process implements. Phytovolatilization is used for chlorinated solvents (such as trichloroethylene, herbicides, insecticides, hydrocarbons, and certain metalloids, such as mercury, arsenic, and selenium. Volatile organic compounds can simply be released into the atmosphere by plants. However, components such as selenium must be transformed in the plant before being volatilized (this transformation simultaneously decreases their toxicity). Mycorrhizal fungi can facilitate the absorption of mercury and selenium, two elements that have a gas phase (Glass 1999).

9.2.2.5 Rhizofiltration

This technique can treat the municipal as the industrial wastewater, surface runoff, or water that infiltrates the soil in agricultural areas, leachate from mines and landfills, or contamination of water and underground water. Contaminants targeted include metallic trace elements, radionuclides, selenium, nutrients, certain organic compounds, such as pesticides, or acid mine drainage (Newman et al. 1997).

9.2.3 Phytoremediation by Microorganisms: Phytoremediation Wastewater by Microalgae (Study Case of Urban Wastewater)

The assessment of the treatment of treatment (phytoremediation) by microalgae on wastewater must cover three major axes, namely: agricultural impact, environmental impact, and socio-economic impact. Several socio-economic benefits can be highlighted during the use of this process, which consists of comparing the physicochemical and microbiological quality of the sewage before and after a phytoremediation process by microalgae, namely, bioenergetic benefits, environmental benefits, and economic and social benefits.

9.2.3.1 Bioenergetic Benefits: Valorization of Fatty Acids Produced by Phytoremediation in Biodiesel

Phytoremediation-treated water shows a very important content of lipid constituents. In fact, lipid compounds are present only after the treatment of water by phytoremediation, which highlights the importance of this process already applied in this research; in this case, the use of this high lipid content in the production of biodiesel (a third generation biofuel). On the other hand, no fatty acid has been detected with the exit wastewater already treated in the treatment plant. In fact, microalgae have greater treatment potential than has been planned and can eliminate many nutrients from water, with greater efficiency than classic wastewater treatment. From an economic point of view, it seems that it would be more interesting to use these microorganisms in secondary rather than tertiary treatment. In particular, the cost of electricity energy supplied and usable during secondary treatment in a station can be replaced by energy produced in biodiesel.

9.2.3.2 Environmental Impact and Agricultural Impact

Purified waters already treated with phytoremediation are devoid of heavy metals and are rich in phosphorus and nitrogen, which constitute a good irrigation substrate in agriculture and can bring out several positive impacts on the environment, on the economy and society.

9.2.3.2.1 Environmental Benefits

Wastewater treatment by the phytoremediation process can reduce the environmental impact of polluted wastewater discharges too loaded into the Gulf of Gabes. Similarly, this treatment can contribute to the improvement of the quality of bathing water and the regeneration of the Gulf of Gabes Marine Ecosystem. In addition, we can observe a sharp fall in the contents of minerals and heavy metals, particularly cadmium and chromes which are completely eliminated after the application of this method. In fact, the elimination rate reaches 100%. Another time, it is observed that the purpose of phytoremediation has been successfully achieved. In fact, the treatment of wastewater by microalgae is in perfect harmony with respect to the environment and offers advantage a cost-effective means of elimination of nutrients and biomass production (Rajhi et al. 2020; Fig. 9.1).

The Gulf region of Gabes has different environment characteristics, namely, a climate with very high humidity and wealth in light intensity (a fairly important light whose presence was continuous throughout the year). Similarly, the region of Gabès has long suffered an important amount of polluted water highly charged with organic materials and which come from the release of wastewater partially treated directly into the sea as well as chemical waste such as the phosphogypse that are rejected with big quantities in marine waters by the industrial zone (Rajhi et al. 2020). This will necessarily allow large-scale recycling of waste in the region, with the resulting environmental and energy benefits. Experimental research already carried out in this study was very close to natural weather parameters of the region defined by an annual temperature of 18.56 °C a year and an average overall solar radiation of 207.1 (w/m^2). The batch experimental parameters are defined by a temperature of 25 °C and a luminous intensity of 100 W. CO_2 and phosphorus, which are key factors in fatty acid production, come from industrial zone which is a few meters from the wastewater treatment

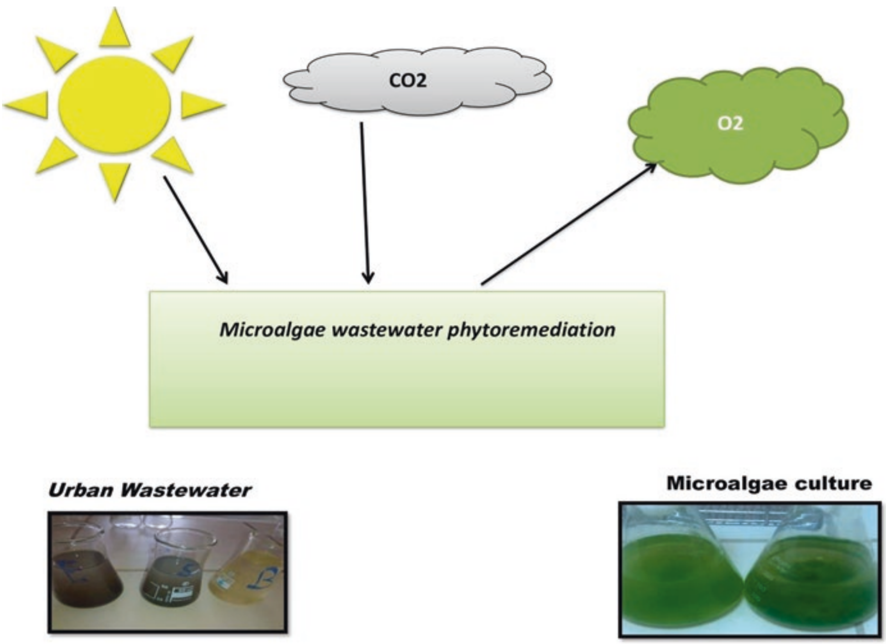

Fig. 9.1 Simplified process of urban wastewater treatment by microalgae enrichment

station. In fact, strategic conditions described above can facilitate a very effective and large-scale natural treatment (Rajhi et al. 2020).

9.2.3.2.2 Advantage of Agronomy

The reuse of treated sewage that is devoid from any chemical, organic and biological contamination in the soil irrigation can constitute an important agronomy challenge (Rajhi et al. 2020).

9.3 Biological Treatment of Industrial Wastewater

9.3.1 Biological Treatment of Industrial Wastewater [Case Study of Olive Mill Waste Water (OMW) Treatment in Arid Zone]

A complete study was made on the olive mill wastewater (OMW) in the South Tunisian for their valorization. The study included the chemical and microbiological characterization of two types of margins: fresh OMW (FOMW), directly from the extraction oiler to a three-phase continuous system, and the other deposited in evaporation ponds (DOMW). The purpose of this natural treatment was to consider ecological assets of the arid region. This comparative study was followed by an assessment of the spreading of these two types of OMW on the soil fertility of the olive field. In addition, an essay of FOMW's strengths in antibacterial activity against standard clinical bacteria. Indeed, a significant increase in pH value of 6 was recorded after the margin layout in evaporation ponds. A fall of the CE to 8.94 A ms/cm-1 was recorded after the OMW layout more than 1 year in evaporation ponds. This fall has been accompanied by a fall in biological oxygen demand (BOD5) and chemical oxygen demand (COD) of 61.05 and 116.37 (G/L) to 55.67 and 103.82 (G/L), respectively. In addition, a significant increase in degradation of phenolic compounds and lipids has been observed after the arrangement of OMW in evaporation ponds. A comparative ground comparative study with OMWF and OMWD shows significant soil fertility after ground spreading with DOMW. The ground treated with DOMW showed an important organic matter compared with the ground treated with FOMW. Indeed, we note that the irrigated site with DOMW has shown [an important value of the germination index (170.55%)] compared with it found in the irrigated soil with FOMW (61.65%) (Rajhi et al. 2018) (Fig. 9.2).

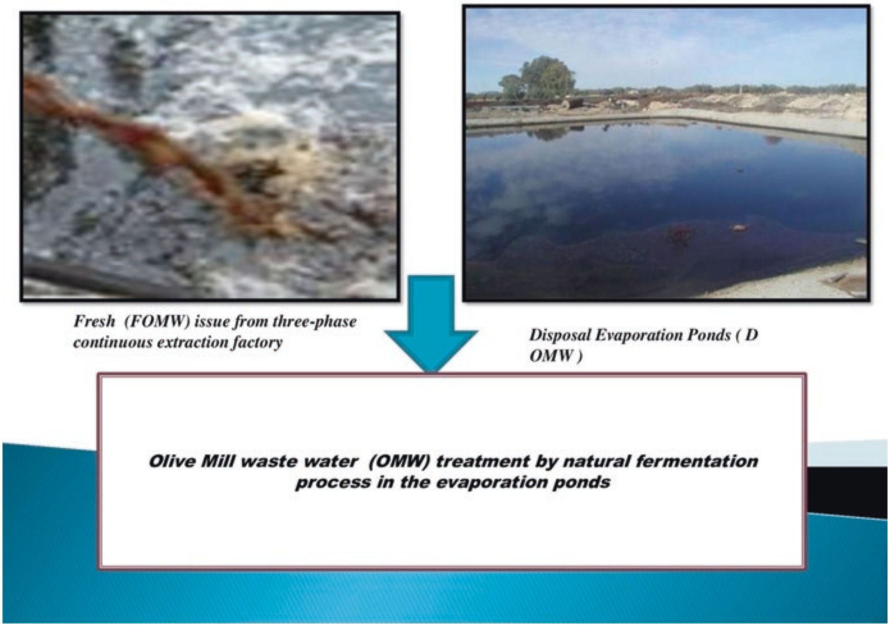

Fig. 9.2 Olive mill waste water (OMW) treatment by natural fermentation process in the evaporation ponds

9.3.2 Biological Treatment of Industrial Wastewater (Case Study: Anaerobic Biodegradation of Chlorinated Organics in Bioaugmented with **Desulfitobacterium spp.**”)

The biodegradation of 2,4,6-trichlorophenol (246TCP) was studied using a reactor (EGSB) and a reactor (FBBR) filled with activated carbon. The result of FISH shows that the methanogenic arrow community has been maintained in the EGSB reactor, while in the FBBR reactor, this community has been gradually developed up to its final stability threshold. The desulfitobacterium community has also been maintained in reactors, although the proportion of D. chlororespirans has increased in the FBBR reactor, which explains that this species can withstand the toxicity of 246TCP and this best that the species *D. Hafniense* (Puyol et al. 2011).

9.3.3 Biological Treatment of Industrial Wastewater (Case Study: Anaerobic Treatment of Wastewater from Used Industrial Oil Recovery)

A study of "Anaerobic Treatment of Wastewater from Used Industrial Oil Recovery" focused on the anaerobic biodegradation of wastewater of residual industrial oils. Biodegradability tests have shown that these wastewater can be partially biodegradable under anaerobic conditions at a mesophilic temperature. Anaerobic treatment using an EGSB reactor has occurred as an optimal option for wastewater treatment. Long-term treatment has allowed the diversity of granular mud, thus modifying and considerably its microbial composition. Methane production was even stimulated by the addition of wastewater at low concentrations.

(Garcia-Mancha et al. 2012).

9.3.4 Biological Treatment of Industrial Wastewater (Case Study of OMW Treatment)

The valorization of by-products of the olive tree to produce on the one hand, a livestock food with high energy value, and on the other hand of the high industrial and biotechnological enzymes, and by the fermentation in solid medium, from the isolated mushrooms of olive by-products. Through this research action, an essay can offered a new way to the valorization of three coproducts of the olive tree at the same time, namely, the size, the OMW, and numbers, and this by the use of new processes which is the fermentation in solid medium, and which is defined as a fermentation or a culture of microorganisms on a solid medium or substrate in the absence of free water. Similarly, by this research, action has been treated the detoxification of effluents of oils in particular OMWs, which already have serious environmental problems that are mainly attributed to the presence of recalcitrant compounds difficult to degrade, such as phenolic compounds, in high concentration (4–15 $G.L^{-1}$), and which are responsible for phytotoxic and antimicrobial effects.

OMW is rich in organic matter especially phenolic compounds and has an acidic pH. As a result, OMW require different processing technologies to eliminate pollutant agents with harmful effects on the environment. In this work, a comparative study was conducted between the chemical treatment of the OMW by the (fenton-similar) method and another biological treatment. Ten species of fungi were used from margins from different trituration units. Three species, namely, *Rhizopus Oryzae*, *Aspergillus Niger,* and *Commune Penicillium*, have been chosen to treat OMW through a biological process. Different inoculum concentrations of these species have been used to determine the most optimum inoculum for more efficient biological treatment. Results obtained have shown that the biological treatment of OMW appears to be the most effective as the chemical treatment. In fact, most isolated mold species showed a significant decrease in phenolic compound contents.

Similarly, chemical oxygen demand (COD) and the rate of OMW discoloration have been very important particularly with the highest suspension of spores, in this case (10^7spora/ml). The *Rhizpous* Oryzae species showed a higher discoloration rate of the order of 82%, which led to an oxidation of phenolic compounds of 6, 5–3.1 g/l and a degradation of the COD of 72.7%.

9.3.5 Biological Treatment of Industrial Wastewater (Environmental Bioremediation by Lipopeptides Biosurfactants Microorganisms Produced)

Biosurfactants are mainly produced by microorganisms growing aerobically, using one or more carbon sources, such as carbohydrates, oils, or hydrocarbons. These microorganisms are usually yeasts, fungi, or bacteria. The main physiological role of biosurfactant is to allow microorganisms to grow on substrates insoluble by reducing the interfacial tension between the water and the substrate, making the latter more easily accessible to cells. Biosurfactant-producing microorganisms have been isolated from a large diversity of environments, including soil, seawater, marine sediments, fields of oil, and even extreme environments. Many extremophilic microorganisms are found in several media marine extremes, such as hydrothermal vents, hot springs, salt lakes, and deep sea floors. The ability of these microorganisms to tolerate temperatures, extremes, salinity, and pressuredemonstrates their great potential for processes biotechnology. Bacterial genera known to produce biosurfactants include *Pseudomonas, Bacillus, Mycobacterium, Nocardia, Flavobacterium, Corynebacterium, Clostridium, Acinetobacter, Thiobacillus, Serratia, Arthrobacter, Alcanivorax, and Halomonas* (Mnif et al. 2021). Although many species produce biosurfactants, the regulation of their synthesis is still poorly understood, except for strains of Pseudomonas aeruginosa and Bacillus subtilis which are the most studied bacteria (Mnif et al. 2021).

9.4 Bioremediation and Bioenergy of Sludge and Sediments

Many policies were interested in the problem related to the reduction of fossil fuel reserves and prospects of climate change that makes the search for the source a priority of renewable new energy vectors; especially, in recent years, we see a serious environmental change, such as (I) global climate change, (II) depletion of fossil fuel reserves, and (III) increasing quantities of waste caused by the high industrial activity and the highest population growth in urban areas (IV). A strong increase in energy demand and a pressing needs for alternative energy (Rajhi 2012).

Hydrogen, nowadays, represents one of the most promising sources of renewable energy. It is currently produced by very intensive thermal and electrochemical processes; this refers to the need for high energy consumption which is associated with the growing demand for the use of other non-renewable energies. There are two possible mechanisms for this biological production of hydrogen, namely, the reduction photo and the obscure or acidic fermentation.

Among the most important benefits of this organic hydrogen production, it can be evoked at the same time its high efficiency and low cost. Nevertheless, this production may encounter a major problem during its realization which may be due to the partial pressure of hydrogen. Indeed, if this pressure reaches very high values, hydrogen-producing bacteria (such as clostridium) may change their metabolism by driving either a mere reduction of this hydrogen production is its total removal. A study realized by Rajhi 2012 proposed the production of hydrogen by organic fermentation using isolated and identified bacteria, and to solve if it comes to the problem of inhibition or change of bacterial metabolism that is necessarily to influence this hydrogen production. Optimizations of different parameters were fixed in goal to promote an efficient hydrogen production, such as pH, substrate and temperature. Results of this study will eventually be applied at a reactor that will be enriched by hydrogen-producing bacteria. This reactor will be useful for the purification of wastewater, and at the same time, the production of hydrogen under the most optimal conditions is possible.

The original approach of this work consisted in avoiding the accumulation of H_2 by its extraction by applying the void. During anaerobic digestion of organic matter, hydrogen produced is consumed by hydrogen consumers, mainly Methanogenic archèes. This is why, moreover, that to obtain H_2 as a final product, methanogenesis (biomethanation) must be avoided. Regarding the choice of inoculum, the production of biomass and solid and liquid waste draws special attention insofar as it can transform a large quantity of organic waste into energy resources.

In this study, an isolation of hydrogen producing species from several sources, such as an anaerobic granular mud of an anaerobic Sludge BED (U.A.S.B) reactor, an anaerobic digestive mud Municipal solid waste, an activated domestic treatment plant, and anaerobic sediments of a river (Rio Tinto, in the south of Spain). In addition, optimization of pH and the temperature on H_2 production by isolated species and by enrichment culture are also presented and discussed. Intermediate dark fermentation products have also been examined (Figs. 9.3 and 9.4).

All species isolated in this work belong to the genus *Clostridium*. These bacteria are metabolically universal, and capable of using a wide range of carbon sources. In addition, *K. pneumoniae*, *C. Kluyveri,* and *C. bifermentas* have been identified, using different culture media and a granular sludge as inoculum. A significant fluctuation in the hydrogen production of one species to another has been observed, which can be explained by the diversity of metabolisms of each species. If we only consider the dco consumed, the production becomes higher than 300 ml h_2 g^{-1} consumed COD, or even higher than 450 ml h_2 g^{-1} COD consumed for *C. diolis* rt2 and *C. beijerinckii* uam, which corresponds to at 2.5–4 mole-h_2-mole of glucose consumed. For most species studied, the optimum pH for the production of hydrogen was 6.5, with the exception of R12 (pH 5.5), H17 (pH 7.5), and H5 (pH 5.5–7.5). In general, the optimum pH allows microorganisms to produce and achieve maximum hydrogen production. Nevertheless, hydrogenase activity in hydrogen fermentation

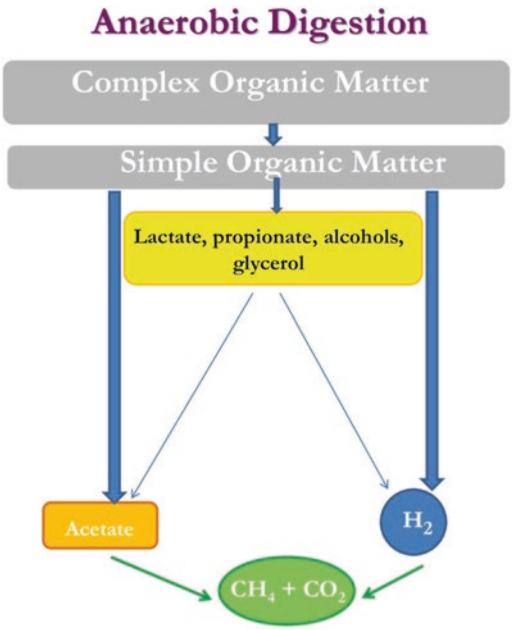

Fig. 9.3 Simplified diagram of anaerobic digestion

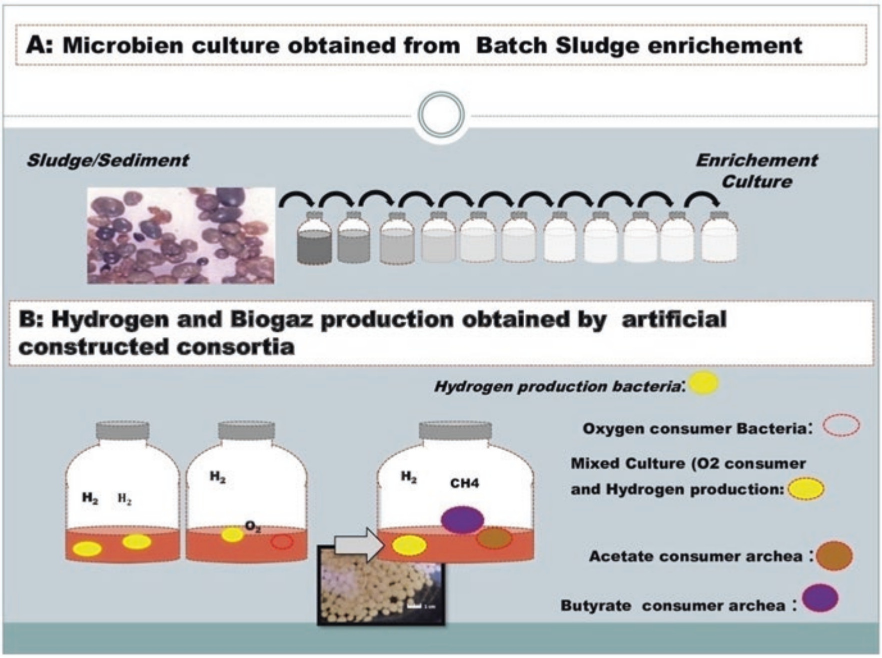

Fig. 9.4 (**a**) Enrichment culture of granular sludge batch culture treatment. (**b**) Bioenergy production (hydrogen and biogas) by microbial consortia

can be eliminated by weak or large pH values. For most species studied and enriched crops, 35 °C was the best temperature for the production of hydrogen except for R12 (30 °C) and H17 (25 °C). For most cases, we note that weak hydrogen production occurred in 25 and 40 °C; this indicates that the production of hydrogen in Clostridium has been removed at a low and high temperature. From then on 40 °C can be considered as a critical temperature in the enriched crop. This explains that a fairly high temperature may terminate some essential enzymes and proteins associated with cell growth and hydrogen production.

The analysis of final fermentation products has shown a butyrate accumulation and acetate. The species H1, H5, RT1, RT2, and UAM made a butyric ferment using the MR medium as a substrate, heterolactic fermentation, or acid-mixed fermentation produced with R14 and R12 using as a substrate. Regarding the *EC*, the butyrate was the most important final product, with the exception of tests made at a temperature of 40 °C, in which the fermentation of lactic acid seems to occur. That the production of hydrogen was made by a butyric fermentation, which constitutes in our view, the typical fermentation of effective production of H_2. Yet, alcoholic fermentation and propionic were observed, respectively, by R6 and H5 using meat extract as a single source of carbon. Note that the amount of fermentation products and the metabolic route depend on both species and changes in metabolism incumbent by changes in temperature, pH, and substrate. Mixed acid fermentation, heterolactic fermentation, propionic fermentation, and butyric fermentation are considered as the most important metabolic roads in this study on the granular mud using different substrates (synthetic environments and industrial and domestic wastewater) (Rajhi et al. 2016).

The hydrogen production can be inhibited at a hydrogen gas pressure more than 0.5 atm. In this context, the hydrogen extraction by vacuum application process is plausible. In fact, results show a positive effect of hydrogen extraction by applying vacuum to the degradation of organic matter and significant changes in metabolic roads. The vacuum application avoids changing acidogenesis toward the fermentation of solvents, associated with the production of hydrogen toward the production of smaller substrates (namely, butanol and ethanol). In all studied tests, the vacuum application has allowed the oxidation of final fermentation and substrate products: which has decreased the final COD. Regarding the emptiness effect in the EC, an increase in bacterial biodiversity has been observed and the disappearance of hydrogenotrophic methanogens. The combination of *C. Saccharobutylicum* H1 and *C. Roseum* H5 shows a significant production of hydrogen which is capable of degrading the complex organic matter containing both carbohydrates and proteins. A consortium includes streptomyces SP. In addition, hydrogen-producing species could allow an accumulation of biomass in a bioreactor and establish anaerobic conditions in the environment without adding any reduction agents. In addition, the introduction of a bacteria likely to degrade the butyrate (*Syntrophobacter Wolinii*) and an archy likely to consume acetate (*Methanosaeta Concilii*) could decrease the final fermentation products (especially butyrate and acetate) and allow methane production (Rajhi et al. 2013a).

9.5 Contribution of Phytoremediation/Bioremediation Processes to Recent Developments in the Economics of Sustainable Development

Bioremediation is a process for the biological treatment of waste, whether liquid (urban or industrial wastewater) or solid (contaminated soil, contaminated sediments, and sludge), using microorganisms. This biological remediation of waste involves microorganisms (generally bacteria, fungi, and microalgae) to decontaminate effluents (liquid and/or solid). Consequently, these microorganisms become main players in this bioremediation technique. These microorganisms through their decontamination of waste can also produce energy (bioenergy), which can be biogas (methane and hydrogen). Likewise, and in the case where these microorganisms are photosynthetic (the case of photosynthetic bacteria and microalgae), a large amount of lipids can be supplied by these microorganisms; these lipids can in turn be converted into biodiesel (we are talking about third generation energy here). This denotes several advantages that can be produced when using the microorganism bioremediation process, namely: socioeconomic and environmental benefits.

Phytoremediation is a process used to decontaminate wastewater, the main players of which are microalgae. Its advantage is that it fixes CO_2 as a greenhouse gas. In general, the treated wastewater by phytoremediation displays an important lipid contain, which evaluates the importance of this bioprocess, notably in this case use of this high lipid compound into biodiesel production (a third generation biofuel). In addition, any fatty acid was detected with the outlet wastewater already treated in the treatment plant. In fact, phytoremediation displays a greater bioprocess potential than classical wastewater treatment method. From an economic point of view, it seems more interesting to use these microalgae phytoremediation in a secondary treatment rather than a tertiary one. Especially, the energy electricity energy cost can be supplied in plant tratemet can be replaced by energy produced in biodiesel. Bioenergy: is a process that consists of biologically treating waste, contaminated sediments, sludge, and wastewater using microorganisms and producing bioenergy (hydrogen and biogas). Using this process (namely, the case of the bioproduction of hydrogen by acid fermentation), we can solve the problem linked to the decrease in fossil fuel reserves and climate change, which make the search for renewable energy sources a priority. In addition, its use in hydrogen-fuel cells makes it a promising alternative to hydrocarbons to power land vehicles. Indeed, nowadays, all the governments of the world agree on the need to put in place policies that allow the development of renewable or alternative energies.

The use of these two bioremediation processes is in perfect harmony with recent developments in the economics of sustainable development in which the environmental costs of growth are taken into account. These techniques can, therefore, be considered as a contribution to research on biological remediation processes for waste resulting from economic activity while highlighting international standards of respect for the environment which aim to preserve the environment and the reduction of environmental costs linked to economic growth.

Indeed, human productive activity has always been accompanied by unexpected health consequences and negative externalities exerting external effects harmful to the environment and disastrous consequences on human health due to high levels of concentrations of polluting elements resulting from of industrial, agricultural, and service production in urban areas. Industrialization policies, for example, implemented for several decades all over the world and have been an important step in the anthropization of the planet and the biosphere through the use of fossil energy reserves and its environmental consequences. Intensive growth has resulted in increasing predation on natural resources offered to us by the planet and harmful effects on the environment. This mode of development can be generalized to all countries when we realize that the growth model of industrial countries has resulted in significant climatic disturbances (global warming, various pollution, and depletion of natural resources) and by an unprecedented degradation of the environment.

Actually, sustainable development has become one of the major challenges of contemporary economies, due to the ecological limits that economic growth faces. The implementation of adequate environmental policies which will be in perfect harmony with recent developments in the economics of sustainable development in which environmental costs of growth are taken into account and whose supporters advocate green growth (green business) and the sustainability of economic development that preserves the environment and safeguards the interests of future generations and improves the well-being of individuals has become the way essential for preserving the environment and restoring the right to life for future generations. Several questions arise at this level, namely: is economic growth compatible with the preservation of the environment? Can the damage of growth on the natural and human environment be repaired? Can we expect economic growth and scientific and technical progress to solve all these problems? Is the market capable of regulating and correcting human behavior in the direction of sustainable development? What policy can the state pursue in favor of sustainable development? Should it encourage economic agents by adopting a tax or subsidy system in favor of “green growth”? Can we set up a “polluting rights” market to limit greenhouse gas emissions? What instruments do the public authorities have to effectively carry out climate and environmental policies? Consequently, the awareness of national political decision-makers on the environmental risks of economic growth and, therefore, of the interest of integrating environmental standards into economic production cycles has paved the way for a new model of governance in management. The environmental constraint weighing on growth and the socio-economic dynamics of development provide an approach method integrating the economic, ecological, and social dimensions.[1]

[1] This trend in the economics of sustainable development shows the extent to which the health-environment field must integrate multiple, different and complementary disciplines, approaches and points of view, in this case the economic, ecological and social dimensions.

9.5.1 Sustainable Development and the Negative Effects of the Economic System on the Environment

Economic development is a qualitative process of transformation of economic, social, cultural, demographic, and mental structures that accompanies and promotes the economic growth of a country. We insist here on the structural (industrialization, urbanization, wage employment, institutionalization, etc.) and qualitative (transformation of mentalities, behaviors, etc.) aspects of long-term development. Development translates into the advancement of the well-being of the population. Human well-being is a qualitative and subjective notion that expresses the satisfaction that an individual derives from life.[2] According to the Brundtland Report of 1987, the sustainable development is "development which meets the needs of present generations without compromising the ability of future generations to meet theirs". It is about having a way of growth that allows the next generation to have at least as much well-being as our own generation, in particular not to (too much) destroy the ecosystem, part of which is non-renewable. In other words, development is sustainable if the capacity of society to produce well-being remains constant. The idea is that an economy must both meet the needs of the present generations (equity in the sharing of wealth at the global level and fight against poverty and hunger) and thus allow their well-being but also allow the generations to future generations can meet their needs and achieve a level of well-being at least equal to the present generations (taking the environment into account in economic calculations). Two implications emerge from the "Brundtland" commission: (i) taking into account the concept of need, and more particularly the essential needs of the most deprived, to whom the highest priority should be given. (ii) Resources are limited: "the idea of the limitations that the state of our techniques as well as our social organization impose on the capacity of the environment to meet current and future needs". Sustainable development, therefore, combines two concepts, namely: development and sustainability. Indeed, according to the theses of the economics of sustainable development, growth and development have several limits: their impact on the environment depletes natural resources and mankind's natural heritage, and at the social level, there is a persistence of inequalities and the social divide remains in many countries, not all countries benefit from growth: persistence of inequalities between developed and developing countries. As soon as we witness the birth of a new concept of sustainable development, that is to say "a development which meets the needs of the present without compromising the ability of future generations to meet theirs" and which advocates solidarity between generations (reduction of

[2] It should be noted that economic development is the expression of a strong and sustained expansion of material production (growth of the Gross Domestic Product (GDP) or of national income) associated with a reduction in monetary poverty and progress in health and education and the universalization of real freedoms. Development is a qualitative phenomenon taking into account the economic and social dimensions, it is measured thanks to the HDI.

greenhouse gas emissions), and between peoples (fair trade), participation of all in the preservation of the environment, precautionary principle (risk prevention).

The Brundtland report advocates a new model of governance in the management of the environmental constraint that weighs on growth and the socio-economic dynamics of development, and this by providing a method of approach integrating the economic, ecological, and social dimensions. Growth is said to be sustainable when it is consistent with sustainable development. Sustainable development is not only about preserving the environment, it must make compatible the creation of wealth, the satisfaction of basic needs, and the preservation of the environment for future generations. Thus, due to the importance of the risk of environmental degradation, in recent years, we have witnessed an awareness of the value of sustainable development or sustainable development which tries to respond to two aspects linked to the degradation of the environment. environment linked to the increasing rate of the level of economic activity and, therefore, to economic growth, namely: sustainable development as a response to the environmental costs of growth (i.e., economic development which seeks to reconcile the economic, social, and environmental dimensions of development) and sustainable development that meets the needs of the present without compromising the ability of future generations to meet theirs. Given that natural resources are irreplaceable and that a preserved environment should be left to future generations.

9.5.2 The Three Pillars of Sustainable Development

The three pillars of sustainable development (Fig. 9.5): (I) the economic pillar: economic development—more equitable place of developing countries in the world economy; (II) the environmental pillar: taking into account the environmental dimension of growth, respect for biodiversity and ecosystems, reduction of polluting emissions, and non-destruction of natural capital; and (III) the social pillar: fight against inequalities and poverty (social consequences of economic activity, problem of inequalities, working, and living conditions).

The concept of sustainable development, therefore, combines three dimensions: economic (creating wealth and improving material living conditions), social (meeting health, education, housing, employment, prevention of exclusion, and intergenerational equity), and environmental (preserve the diversity of species and natural and energy resources). Economists will have to make their contribution in order to present a solution that will reconcile the economic, social, and ecological dynamics of growth. It is a question of answering the question of knowing how countries should proceed in order to be able to increase the well-being of the world population, fight against social inequalities and safeguard the dynamics of the biosphere (Vivien 2008). This debate must be organized around the two concepts introduced by the Brundtland report, namely: the concept of needs and that of limitations. Two theoretical projects have thus emerged: the first focuses on meeting needs, and

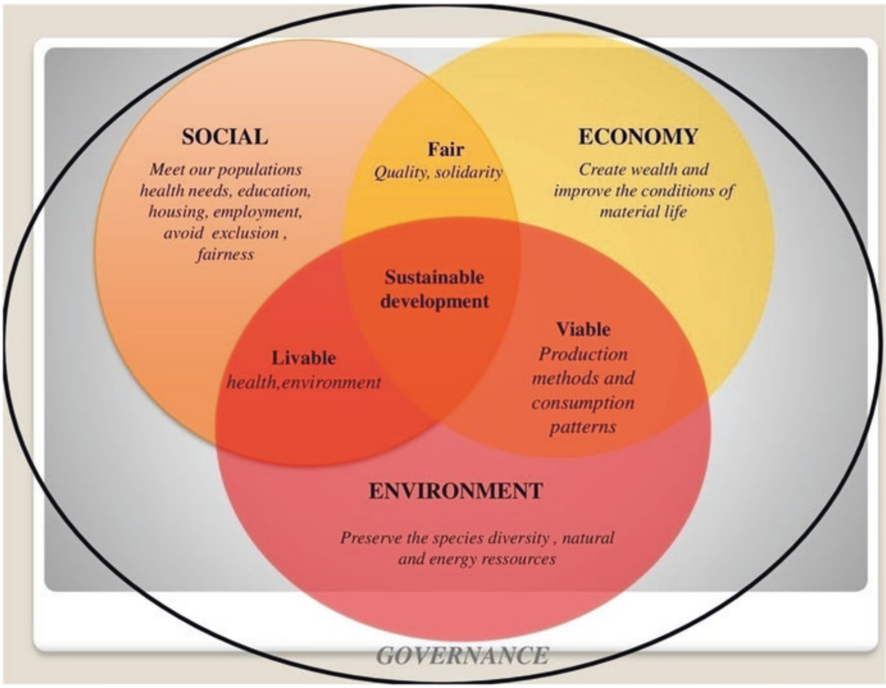

Fig. 9.5 Three pillars of sustainable development

examines the links that may exist between growth and development. The second focuses on the environmental constraint weighing on the socio-economic dynamics of growth.

9.5.3 *Is Economic Growth Compatible with the Preservation of the Environment?*

The economic analysis of sustainable development, which is based on the preservation of development possibilities for future generations, is concerned with the level and evolution of the stocks of each type of capital (accumulation and destruction) as well as the decisive question of the degree of substitution between these different capitals as well as how to overcome the ecological limits encountered by economic growth (depletion of energy resources and fish stocks, deforestation, increase in the concentration of greenhouse gases, etc.). In connection with climate policy, which will make it possible to analyze the instruments available to public authorities to carry out environmental policies in the face of externalities suffered by the environment and market failures?

9.5.3.1 The Economic Growth and Development Results from the Interaction of Several Types of Capital

The economic analysis of sustainable, or sustainable, development emphasizes the preservation of possibilities for future development. By relying on the classic analysis of production in which the product flows result from the mobilization of factors production, such as the productive capital and labor the usual analyzes. It, therefore, broadens the notion of productive capital and adopts a patrimonial approach, which different capital stocks are taken into account. We can thus make a distinction between natural, physical, human, and social and institutional capital. Development, therefore, results from the accumulation of the different four types of capital.

Natural capital brings together the various resources of nature capable of generating a productive service (wealth of the sea, the soil, the subsoil, etc.). It corresponds to natural resources (such as water, soil, coal, oil, fauna, flora, etc.), ecosystems, and biodiversity which provide populations with material well-being or not. It can take the form of a stock of renewable or exhaustible resources which make it possible to produce well-being by its exploitation for productive purposes. Direct source of good to be, it represents the essential support of our life. Some natural resources are non-renewable, others are renewable (regenerate on their own) as long as they are not over-exploited (e.g., fishery resources). The physical capital is a good produced in the past by man and used as a means of production (building, machine, material, etc.). It is the set of means of production, including fixed capital (capital goods) and circulating capital (intermediate goods). This stock of durable goods available to a community is used to produce goods and services capable of meeting the needs of the population and improving their well-being. The progressive wear and tear of this capital are taken into account through the concept of depreciation.

The human capital can also be accumulated by humans and includes the physical and intellectual capacities of an individual or a group of individuals; it can be accumulated through training, initial or professional. It brings together all of: individual wealth made up of know-how, interpersonal skills and knowledge (acquired during initial or continuing training, learning, and social and professional experiences) which provide advantages (particularly in terms of well-being) both individually and collectively. According to G Becker, labor power is capital: it is possible to invest in human capital in order to improve its productivity. It is possible to integrate the level of health into it.

Concerning, the social and the institutional capital: set of social networks, norms, values, and institutions which make it possible to increase trust between the actors in a given society. This increased confidence brings individual interests and collective interests together and thus promotes the well-being of populations. Institutions are the set of human frameworks and constraints that structure political, economic, and social interactions. Legislative apparatus, other norms, formal or informal, values, can contribute to the well-being of populations as well as to economic growth. Institutional capital brings together these institutions. Political, institutional, and legal arrangements, therefore, correspond to institutional capital. These institutions have the following functions: protection (of property, contracts, resources, etc.), surveillance (of competition), regulation (respect for economic balances), coverage (insurance and social protection), and arbitration (of social conflicts). These different types of capital contribute to conventionally measured production and can thus contribute to the well-being of populations. However, they can also contribute in ways that are more difficult to measure. If we take the example of a natural resource, such as the forest, this can constitute a measurable productive capital (exploitation of tree species, firewood, etc.), but also absorb part of the gas production, greenhouse effect (unmeasured productive service), be conducive to hiking (most often non-market productive service) or even arouse the pure well-being or wonder of those who cross it.

9.5.3.2 Sustainable or Sustainable Development and the Debate on the Substitutability of Capital

9.5.3.2.1 Sustainability, Growth and Environment

The notion of sustainability, of economic growth and its link with environmental constraints has become an inescapable necessity that should be realized in the economics of sustainable development. This approach to the sustainability of development makes it possible to ask crucial questions. Is the current global level of production sustainable? Is not the environmental constraint on the growth of wealth so restrictive that it calls into question its viability? To these questions, only one answer emanates from neoclassical economists; the solution is growth. Their argument is based on a theorization leading to an environmental Kuznets curve (Kuznets 1955). The idea behind it is that there is clear evidence that although economic growth normally causes environmental degradation in the early stages, in the end the best—and probably the only—path to regaining a decent environment in the country. Most of the country is getting rich. The environmental Kuznets curve (inverted U) is a possible representation of this notion of sustainability, of economic growth and its link with the environmental constraint responding to the hypothesis of substitutability between capitals. As with social inequalities, polluting emissions would initially increase as average income increases. Second, new "cleaner" technologies would reverse the trend. If we consider the environmental Kuznets curve as a satisfactory representation of the relationship between economic growth and the environment, then not only is growth not contradictory with the preservation of the environment, but, correctly oriented, it is a condition of this preservation. The basic essential elements of this representation of the link between growth and the environment are well-recognized by economists, and the growth of production requires more exploitation of resources and generates more waste and pollutants. The idea is that beyond a certain development threshold, a company will move toward cleaner activities; therefore, the ratio of emissions to the increase in per capita GDP is falling. In other words, as the GDP increases (growth), the rejection rate tends to stagnate. Once this stage has passed, a company has the capacity to invest part of its wealth in the research and development of means of production that are more respectful of the environment, which tends to lower emissions while increasing GDP. These effects would be expressed by principles of social evolution and political demands.

In general, the Kuznets environmental curves can be highlighted in some data concerning some local environmental issues (such as air pollution) but not in others (such as soil renewal or biodiversity). We must also add that the effects of climate change such as the disappearance of species and the loss of biodiversity are irreversible. Although some empirical studies indicate that economic growth may be associated with improvement in some environmental indicators, this does not imply that economic growth is sufficient to improve the state of the environment in general.

9.5.3.2.2 Sustainable Development: Strong Sustainability (or Sustainability)/ Low Sustainability (or Sustainability) Sustainable or Sustainable Development Integrates Three Dimensions

The economic dimension (growth in wealth must be possible), the social dimension (this wealth must be equitably shared in the world and between generations), the environmental dimension (resources and the planet must be preserved). Economic analysis is based on the possibilities for development and improved well-being for future generations; in accordance with the heritage approach adopted, it bases the sustainability criteria on the evolution of stocks of the four types of capital mentioned above. A debate remains on the substitutability[3] of these four types of capital and, therefore, on the means to ensure the sustainability of our development. Two conceptions of sustainable development should, therefore, be distinguished: weak sustainability in which capital is substitutable and strong sustainability in which capital is not substitutable. Those in favor of "weak sustainability" believe that nature is productive capital like any other. Therefore, it can be considered substitutable. If it becomes scarce, its price will become higher and economic agents will strive to find productive technologies that will make more use of other factors of production that have become relatively less expensive. Technical progress can then push back the limits of economic growth. The freedom of agents, which pushes them to seek the optimal technology to produce, may, therefore, be sufficient to ensure the sustainability of production growth and our development. Humans have been able to save and even reintroduce animal species, rebuild endangered natural environments. A polluted river can be cleaned up, a destroyed forest replanted, there reconstituted biodiversity. It suffices to maintain a capacity to produce economic well-being at least equal to that of the present generations. To ensure this, the level of total capital (natural and built) must be kept constant. They consider that damage to natural capital is, to some extent at least, irreversible: the damage caused to the environment remains partly irreparable and certain exhaustible resources are

[3] Sustainability is a situation in which the current level of well-being can at least be maintained for future generations, which supposes measuring the quantitative and qualitative evolution of the stocks of heritage on the basis of our well-being.

irreplaceable. In this hypothesis, it cannot be enough to keep the global capital constant. Natural capital must be the subject of specific conservation. The factors of production are not all substitutable. Technological innovations alone cannot push the limits of economic growth. Indeed, following a very intense production cycle, the evolution of "natural capital" can be compromised by the rise in environmental costs which have become quite significant.

These high environmental costs are linked to the following: (I) excessive drain on non-reproducible natural resources, (II) excessive drain on natural resources or their degradation which leads to an erosion of biodiversity, (III) fairly significant damage linked to pollution (negative externality), while the expenditure for nature protection is very negligible (the expenditure for the treatment of polluted water, for example, is quite low or even non-existent), (IV) the massive use of fossil energy (oil and coal) which contributes to the increase in greenhouse gases and, therefore, to global warming, and (V) atmospheric pollution linked to industrial economic activity and lifestyle, which exerts a negative externality, and increases greenhouse gases, responsible for warming and climate change. In the pessimistic version of the concept of sustainability (strong sustainability (or sustainability), damage to natural capital is, at least to a certain extent, irreversible. Some damage is irreparable, some resources are not renewable, and others are overexploited.

Natural capital must, therefore, be the subject of specific conservation and other capitals cannot be substituted for it, capitals are complementary, that is to say, the use of one type of capital necessarily implies that of other capitals. In the optimistic version of the conception of sustainability (low sustainability, nature is a productive capital like the others, natural capital is, therefore, substitutable, in particular by human capital and physical capital. his price will increase, economic agents will be encouraged to find technologies that save this factor or use other factors (e.g., oil).

The essential idea results from this analysis of the concept and criteria relating to the sustainability of sustainable development (Vivien 2005) is that it is necessary to transmit to future generations the same global capital stock composed of four types of substitutable capital (natural, human, physical, and institutional). It is above all a question of transmitting or preserving to future generations the same stock of natural capital. As a result, natural capital can be substituted for other forms of capital (human, social, and technical which incorporates new technology). In this case, it is up to the state (institutional capital) to promote substitution between different types of capital, for example, by supporting technological changes that save nature, and by educating individuals on the benefits of sustainable development.

9.5.4 What Environmental Policies to Put in Place by Governments?

Environmental degradation and climate change resulting from industrialization (release of pollutants into nature) can be analyzed as pollution which, in economic analysis, corresponds to a negative externality. In such situations, individual economic agents only take into account in their decisions the private costs and benefits of their actions, thus neglecting the costs incurred by humans. Since there is an externality, there is necessarily a market failure in a laissez-faire situation: in the presence of a negative externality, the private cost is lower than the social cost, so that the action at the origin of the externality tends to be chosen excessively with regard to what is socially desirable. In the event of obvious market failures, it will be imperative to intervene by the public authority, which must conduct a climate policy with a view to reducing the effects of pollutants on the environment. It is also desirable that global agreements force countries to conduct the measures. Necessary efforts reconcile their environmental policies to limit the damage caused to the environment, which is not without posing serious difficulties. Several instruments for carrying out climate policies by the public authorities in order to reduce greenhouse gas emissions, since these are responsible for global warming/disruption, given that atmospheric pollution linked to economic activity and to life exerts negative externalities. There are two types of economic instruments for managing the climate issue: some are based on coercion and others on incentive. Negative externalities can in fact be combated by regulation, that is to say coercion, and/or by the implementation of instruments aimed at internalizing them: it is then a question of ensuring that the private costs borne by the producers of externalities include social costs, that is to say the damage suffered by other agents. Two instruments can be mobilized for this internalization of social costs: environmental taxes, which correct the prices of existing markets and "emission rights" markets (polluting rights market), which make it possible to generate a decentralized price for emissions. The taxation of economic activities and the market for rights to pollute are economic tools, where we will encourage economic agents to modify their behavior (consumption or production). It should be noted, however, that each instrument has advantages for some and disadvantages for others (producer, worker, consumer, and state). Nevertheless, it should be noted that these instruments must be combined carefully in order to derive maximum benefit from them and increase their use in efficiency for the preservation of the environment and human health.

9.6 Conclusions

The economics of sustainable development is nowadays one of the major challenges of contemporary economies, due to the ecological limits encountered by economic growth. The establishment of adequate environmental policies (climate policies, regulations, taxes, etc.) in which the environmental costs of growth and the negative externalities resulting from industrialization and consequently the sustainability of economic development which will be taken into account, preserves the environment and safeguards the interests of future generations and improves the well-being of individuals, has become an essential necessity for national and international political decision-makers in the search for economic, ecological, political, and social solutions for the preservation of the environment and the restoration of the rights to life for future generations. The use of bioremediation and phytoremediation processes to remedy pollution and environmental degradation is nowadays one of the favorable and serious solutions which seek to put in place adequate bioenergy policies likely to preserve the environment. These processes are correct with economic sustainable recent developments in which the environmental growth costs are taken into account. These techniques can, therefore, be considered as a contribution to research on waste bioremediation bioprocess resulting from economic activity while highlighting international standards of respect for the environment which aim to preserve the environment.

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