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PHENOLS TRANSFORMATIONS IN THE ENVIRONMENT AND LIVING ORGANISMS

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Phenols are the organic compounds, which possess hydroxyl residue at first position of carbon within the aromatic ring. These compounds are widely represented in natural environment. Most of the phenols show negative action towards living organisms including humans. The presence of these compounds in the biosphere lead to their transformation undergoing under the influence both abiotic (the activity of bacteria, fungi, algae, some higher plants) and abiotic (metal oxides - MnO, Fe_2O_3, clays, radiation) factors. The transformation processes most often lead to the total degradation (mineralization) of these compounds. The possibility of phenols degradation by microorganisms is due to creation of enzymes capable to transform phenolic xenobiotics and use them as the source of aliment and energy. When phenols reach the human organism undergo detoxication processes leading mainly by microoxidases within the cytochrome P450. The reactions lead to inactivation of phenols by oxidation and binding them with sulphates, glucuronide acid, glucose and aminoacids what increase the solubility of phenols in body fluids and finally lead to the efficient excretion of these compounds out of the organism. Both in the environment and in living organisms some transformations may lead to creation of most harmful products of these processes.

INTRODUCTION

Phenols due to their toxicity, persistence and common occurrence in the biosphere are one of the most important group of ecotoxins. These compounds are in a common use such as ingredients (components) and precursors of other chemicals including organic polymers, solvents, dyes (aminophenols), explosives (nitrophenols), surfactants (alkylphenols) or drugs (Kahl et al., 1997). Chlorinated phenols and chloroguaiacols are also formed during paper production in a process of (chlorination) bleaching of wood pulp (Knuutinen, 1982). The occurrence of phenols in the environment is also related to production and degradation of many pesticides, eg. phenoxyherbicides like 2,4-dichlorophenoxyacetic, dinoseb acid or phenolic biocydes such as 4-chlorophenol or pentachlorophenol (Laine, Jorgensen, 1996).

Many microbes such as bacteria and fungi are capable to degrade phenolic compounds and use them as a source of carbon and energy.

The capacity of biodegradation is related to adaptation of microorganisms to new habitats. Adaptation is mainly related with synthesis of new enzymes (Sleeger, Stanier, 1950) capable to transform even harmful xenobiotics. Many investigations have revealed relations between structure of individual compound and its susceptibility to degradation. It was reported that number of hydroxyl residues within aromatic ring (excluding catechol) increases resistance of degradation. Likely, substitution of phenol with chlorine atoms also decreases transformation effectivity of xenobiotics by bacteria. Reversely, addition of methyl residues facilitates enzymatic "attack" towards phenols (Taba, Chambers, 1964). Susceptibility of phenolic compounds to biodegradation is given below: para-nitrophenol > 2,4-dichlorophenoxyacetic acid > pentachlorophenol (Ingerslev, Nyhlom, 2000).

BIODEGRADATION OF PHENOLS BY PROCARYOTIC ORGANISMS

Phenol

Microbiological biotransformation of phenol lead to formation of catechol, hydroxyquinone or benzoic acid. Disscussing compounds are then cleavaged in 2-oxoadiapate and 3-oxoadiapate metabolic pathway (Clauâβen and Schmidt, 1998). Phenol is mainly transformed to catechol. This process is performed by bacteria like *Alicagenes*, *Achromobacter*, *Pseudomonas sp*., *Pseudomonas sp.* CF 600, *Pseudomonas putida*, *Pseudomonas picketii* and *Acientobacter calcoaceticus* (Schirmer et al., 1997). Transformation of phenol to benzoic acid is mainly leaded by *Clostridum hastiforme* and *Desulfobacterium phenolicum.* Phenol is also transformed by clusters of *Alicagenes* and numerous representatives of *Flavobacterium* (Watanabe et al., 1996) and *Geobacter metalireducens*. Biotransformation of phenol is also performed by bacteria such as *Comamonas sp*. E6 (Watanabe et al., 1998), *Psudomonas fluorescens* (Becker et al., 1998) and *Pseudomonas syringae* (Erhan et al., 2004). Transformation of phenol with high effectivity is also leaded by *Agrobacterium radiobacter*, *Staphylococcus siuri* and *Pseudomonas diminuta* (Kowalska et al.,

1998). The another taxon *Synechococcus* PCC 7002 that belongs to cyanobacteria is also capable to degrade phenol. The activity of this species lead to formation cis-, cis-muconic acid that is formed during ring cleavage of the compound (Wurster et al., 2003). Bacteria are also able to mineralize phenol to use it as a source of carbon and energy. The examples are *Desulfobacterium* (Häggblom, 1998), also *Pseudomonas cepacia* (Schroder et al., 1997), *Halomonas* (Hinteregger and Streichsbier 1997) and thermophilic aerobic bacteria *Bacillus sp.* that cleavages phenol in meta position (Milo et al., 1997). Phenol is also degraded by *Ralstonia eutropha* JMP 134, *Rhodococcus rhodochrous* 116, *Pseudomonas sp.* HH 693 and RW 1, *Sphingomonas sp.* RW 1 (Beyersdorf-Radeck et al., 1998), *Arthrobacter chlorophenolicus sp*. DSM 12829 (Westerberg et al., 2000), *Alicagenes xylosoxidans* and *Klebsiella pneumoniae* (Boháčová et al., 2001). Degradation of phenol is also performed by *Alicagenes faecalis* and is leaded by phenol hydroxylase and catechol dioxygenase. Those enzymes hydroxylate and cleavage phenol in orto position and finally mineralize disscussing compound (Bastos et al., 2000).

Chlorophenols

Halogenated aromatic compounds including chlorophenols are transformed by elimination of chlorine atoms in the proccess of reductive dechlorination. Elimination of chlorine atoms makes possible transformation and thus mineralization of chlorinated phenols. The example is degradation of 4-chlorophenol and pentachlorophenol that proceeds by elimination of chlorine atom in para position. This process also concerns 4-chloro-3-fluorophenol and 4-chloro-2-fluorophenol that are degraded by bacteria to respective fluorophenols (Häggblom, 1998). The next step in chlorophenols degradation refers to chlorocatechol formation in a hydroxylation reaction. Direct transformation of halogenated phenols to halogenated catechols also proceeds with simultaneous substitution of one chlorine or fluorine atoms with hydroxyl residue a molecule of degraded compound. Describing process was observed in *Rhodoccoccus opacus* 1G and is called as oxidative dehalogenation (Bondar et al., 1991). *Psudomonas putida* transforms chlorophenols substituted in para positions to 4 substituted catechols and chlorophenols substituted in meta position to 3-substituted catechols (Hinteregger et. a., 1992). The another bacteria *Rhodococcus opacus* 1CP is capable to transform 2-chlorophenol, 4-chlorophenol and 2,4-dichlorophenols to respective chlorinated catechols (Moiseva et al., 2002). The another example is microbiological degradation of 2,4-dichlorophenoxyacetic acid that goes by elimination of side-chain of the compound to form 2,4-dichlorophenol that is finally transformed in orto-hydroxylation procces to chlorocatechol. Other microbes that are capable to transform and degrade chlorophenols are *Mycobacterium fortuitum* and *Streptomyces rochei* (Golovleva et al., 1992), also *Sphingomonas sp.* P5 (Rutgers et al., 1996), *Herbaspirillum chlorophenolicum sp*. nov (Im et al. 2004) and *Anaeromyxobacter dehalogens* (He and Sanford, 2002). *Pseudomonas* sp. 01 and *Pseudomonas* sp. 02 are able to transform 2,4,6-trichlorophenol in the presence of some other chlorinated phenols (Wang et al., 2000). The above mentioned compound is also transformed and mineralized by *Sphingopyxis chilensis* S 37 (Aranda et al., 2003). Cluster of *Alcaligenes eutrophus* JMP 134 can degrade 2,4-dichlorophenoxyacetic acid, also 2,4,5-trichlorophenol, 2,4,6-trichlorophenol and 4-chlorophenol (Valenzuela et al., 1997). 2-chlorofenol, 3-chlorofenol, 4-chlorofenol, 2,3-dichlorofenol, 2,4-dichlorofenol, 2,5-dichlorofenol, 2,6-dichlorofenol, 3,4-dichlorofenol and 3,5-dichlorofenol are degraded by *Sphingomonas sp.* RW 1 (Beyersdorf-Radeck et al., 1998) and 4,5,6-trichloroguaiacol is degraded by *Bacillus subtillis* IS 13 (Andretta et al., 2004). Pentachlorophenol (PCP) is the most often investigated compound due to its strong toxicity and common use as a pesticide. Degradation of pentachlorophenol may procceed in some ways. Firstly, PCP may be transformed in a reductive dechlorination reaction to chlorophenols of lower number of chlorine atoms (from tetrachlorophenol to phenol) (Juteau et al., 1996). Pentachlorophenol is also transformed in a O-methylation proccess to form pentachloroanisole. Finally, PCP may be converted to tetrachlorocatechol during oxidative dechlorination proccess. Pentachlorophenol is also degraded by *Sphingomonas chlorophenolicum* that produces tetrachloro-hydroquinone dehalogenase to tetrachloro-quinone, trichlorohydroquinone and finally dichlorohydroquinone in a reductive dehalogenation reaction (Anandarajah et al., 2000; Cort and Bielefeldt, 2000). Tetrachlorohydroquinone is also the main product of pentachlorophenol transformation in a reaction leaded by *Sphingobium chlorophenolicum* (Dai et al. 2004). Soil bacteria *Bacillus megaterium* also degrades pentachlorophenol at the participation of dehydrogenase (Mc Grath and Singleton, 2000).

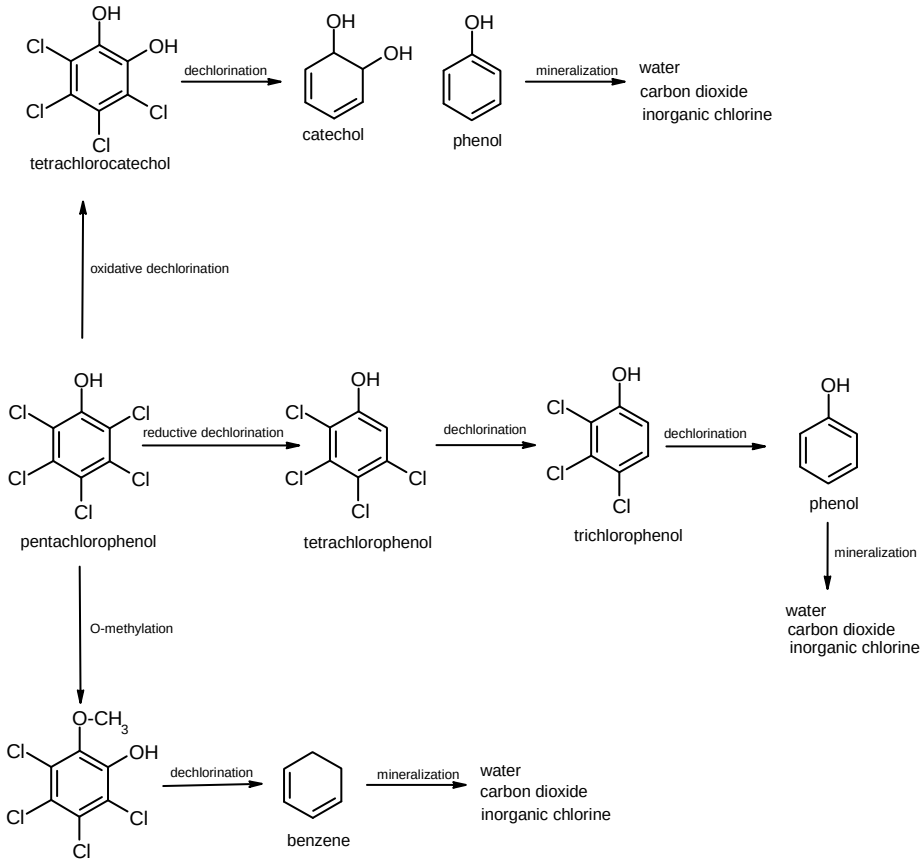

Fig. 1. Environmental transformations of pentachlorophenol.

Catechols (chlorocatechols)

Catechols are formed both by oxidation of phenol and also degradation of benzoic acid and its derivatives. In the environment catechols are biodegraded by *Pseudo-monas* sp. and *Bacillus pumilis.* Degradation is based on oxidative cleavage of aromatic ring by enzymes like catechol 1,2-dioxygenase and catechol 2,3-dioxygenas.

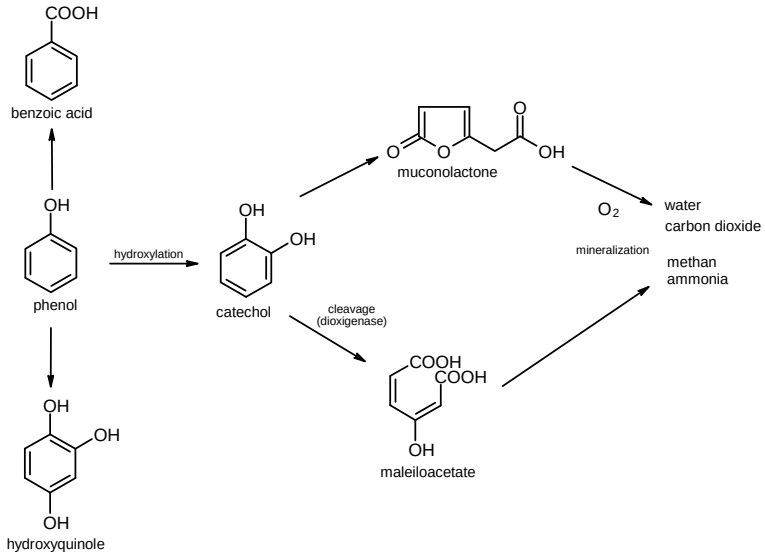

Fig. 2 . Environmental transformation of phenol.

The enzymes involved in these reactions cleavage aromatic ring between first and second carbon (intradiol cleavage) and between second and third carbon (extradiole cleavage) (Ito and Que, 1997). The first reaction leads to formation of maleiloacetate and the second lead to formation of muconolactone**.** The results of investigations also revealed that aromatic ring may be cleavaged between third and fourth and also fifth and sixth carbon within phenol molecule. Products of phenol degradation undergo minerali-zation to yield water and carbon dioxide in aerobic conditions and methane in anaerobic condtions. Catechols are also transformed by ortho and para-diphenol oxidases to form ortho-chinones (Jagoe et al., 1997).

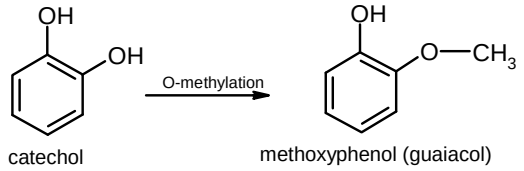

Fig. 3. O-methylation of catechols.

The important role in chlorocatechols transformations plays O-methylation proccess that is based on substitution of hydrogen atom with methyl residue within hydroxyl residue in phenol molecule. This process may lead to formation of methoxyphenols eg. guiacols (2-methoxyphenols) and syringols (2,6-dime-thoxyphenols).

Methylphenols, nitrophenols and alkylphenols

Methylphenols may be transformed to carboxylic acids. For example 2,4,6-trimethylphenol is degraded by *Comamonas sp*. and *Pseudomonas sp*. to 4-hydroxy-3,5-dimethyl benzoic acid (Hofrichter et al., 1995). Methylphenols may be also converted to hydroxyquinones and parabenzoquinones. The compounds like ortho, meta and paracresol are also degraded by *Pseudomonas fluorescens* and other bacteria from *Pseudomonas* genera (Kazumi et al., 1995). Methylphenols are also degraded by *Bacillus thermoleovorans* (Duffner and Müller 1998) and *Pseudomonas putida*. The results clearly evidenced that bacteria are capable to use methylphenols as a source of carbon and energy in a mineralization process. The example is a thermophilic bacterium – *Bacillus sp* capable to degrade orto and paracresol to form methane. Bacteria are also capable to degrade high concentrations of phenolic xenobiotics. In an experiment *Pseudomonas sp*. degraded high concentrations (1000 mg/L) of cresols and meta-cresol was degraded with highest effectivity. *Psedomonas sp* CP4 also mineralizes all isomers of cresols by meta-cleavage of aromatic ring. The ratio of degradation of the isomers is presented: ortho > para > meta-cresol.

Resistance of nitrophenols for degradation rise with increasing number of nitro groups within phenolic ring. 2,4-dinitrophenol undergoes microbiological degradation almost in 90% to other compounds and within 15 days is totally mineralized. Para-nitrophenol is degraded by *Rhodococcus sp*. PN1 to 4-nitrocate-chol at the participation of 4-nitrophenol hydroxylase. Nitrophenols are also transformed by *Sphingomonas sp*. UG30 (Zablotowicz et al., 1999) that transforms 2,4-dinitrophenol and 4,6-dinitro-cresol. Para-nitro-phenol is also degraded by *Rhodococcus opacus* SAO 101 and *Geobacillus thermoglucosidasius*, *Ralstonia eutropha* and *Arthrobacter* sp. (Kitagawa et al. 2004). 2,4,6-trinitrophenol is degraded by *Rhodococcus opacus* HL PM-1 (Nga et al., 2004; Heiss et al., 2003) and *Nocardioides simplex* FJ2-1A (Hofman et al., 2004). Phenol nitration procceds at the participation of *Nitrosomonas europaea* (Saraswat et al., 1994) and denitrification of 2-nitrophenol is performed by *Pseudomonas putida* B2 (Zeyer and Kocher, 1998). *Arthrobacter simplex* degrades pesticide – 2-methyl-4,6-dinitrophenol (DNOC) to form 3-methyl-5-nitro-catechol and 2,3,5-trichlorotoluene. *Rhodococcus erythropolis* mineralizes 2,4-dinitrophenol to nitrogen and carbon dioxide. Mineralization of 2,4-dinitrotoluene by *Burkholderia cepacia* R34 in aerobic conditions leads to formation of 2,4,5-trihydroxytoluene that is finally cleavaged by catechol 2,3-dioxygenase (Johnson et al., 2000). Mononitrophenols are trans-formed by *Moraxella* that degrades para-nitrophenol (Leung et al., 2000). It was reported that *Sphingobium amiense* is capable to degrade harmful toxin – 4-nonylphenol (Ushiba et al., 2003). This compound is also degraded by *Sphingomonas sp*. in a concentration of 4,3 mg/L in 24 hours. Effective mineralization of 3- and 4-substituted alkylphenols performs *Pseudomonas sp*. KL28 that produces phenol hydroxylase and 2,3-dioksygenase (Jeong et al., 2003).

BIODEGRADATION OF PHENOLS BY EUCARYOTA

Fungi

Fungi are capable to efective degradation of phenols due to the activity of their lignolitic enzymes. The results of numerous researches have

revealed that yeasts are capable to transform and mineralize xenobiotics. *Candida maltosa* SBUG 700 in mixed cultures with bacteria degraded pentachlorophenol to chlorophenols of reduced number of chlorine atoms. Formed in a reaction mono and dichlorophenols were degraded to water and inorganic chlorine atoms (Juteau et al., 1995). Chlorophenols are often transformed by yeasts to chlorocatechols (Hammer et al., 1996) and finaly mineralized to water and cabon dioxide. *Candida maltosa* is capable to mineralize high concentrations (1,5 - 1,7g/L) of phenol and catechol. (Fialova et al., 2004). *Aureobasidium*, *Rhodotorula* and *Trichospon* transforms catechol by cleavage of the aromatic ring between first and second position at the participation of catechol 1,2-dioxygenase and phenol hydroxylase (Santos and Linardi, 2001).

A fungus *Scedosporium cepiospermum* transforms phenol and p-cresol to form catechol, hydroquinone and finally water and carbon dioxide (Claussen and Schmidt, 1998). The another species *Lentinula edodes* transforms pentachlorophenol in reductive dehalogenation and O-methylation reactions and mineralizes disscussing xenobiotic (Okeke et al., 1997). The species also degrades chlorinated aminophenols and chlorohydroquinone (Staz et al., 2002). Biotransformation of chlorophenols to chlorocatechols also proceeds at the participation of mushroom *Hypholoma elongatum* (*Basidiomycetes*) (Hofman and Schauer, 1998*). Plerotus ostraeatus* is able to transform harmful ecotoxin – bisphenol A. In an experiment (*in vitro*) bisphenol A was degraded with high effectivity (80%) during 12 days of incubation (Mirano et al., 2000). The other species *Plerotus pulmonarus* dechlorinates and mineralizes high concentration (100 mg/L) of pentachlorophenol (Law et al., 2003). The species that has probably the highest capacity of xenobiotic degradation is *Phanerochaete chryso-sporium* that uses lignin peroxidase to degrade pentachlorophenol. The procces of PCP degradation begins by formation of tetrachloro-1,4-benzochinone that is reduced to tetrachlorodihydroxybenzene or transformed to 2,3,5-trichlorodihydroxybenzene. Tetrachlorodihydroxybenzene is converted in a process of reductive dechlorination to 1,4-hydro-chinone and then that is mineralized to carbon dioxide and water. (Reddy and Gold, 2000). *Phanerochaete chrysosporium* and *Trametes versicolor* produce para-diphenol oxidase the enzyme that degrades lignin and forms guaiacols and syringols from other phenols (Grey et al., 1998). *Trametes versicolor* participates in a biodegradation process of 2-chlorophenol to 2-chloro-1,4-benzoquinone due to avtivity of para-diphenol oxidase. *Trametes versicolor*, *Abortiporus biennis, Cerrena unicolor i Gloephyllum* dependly on the presence of different substrates eg. 2,5-dimethyl-aniline, metabolize chlorophenols with different effectivity. The highest effectivity of degradation reveals C. unicolor that degrades pentachlorophenol in 1 hour with 98% effectivity (Cho et al., 2001). *Phanerochaete chrysosporium* is capable to mineralize 2,4-dichlorophenol, 2,4,5-trichlorophenol and pentachlo-rophenol at the participation of manganese peroxidase (Grey et al., 1998). *Cunninghamella elegants*, *C. echinulata*, *Rhizoctonia solani* and *Verticillium lecanii,* are also capable (in the presence of nitrogen and glucose) to transform phenols like 2,4-dichlorophenol and 2,4-dichlorophenoxyacetic acid (Vroumsia et al., 1999). *Mortierella* converts phenol and three isomers of cresol in high concentration of 150 mg/L in low temperature (4°C) (Peron and Welander, 2004). The capacity of mineralization of phenol also reveals *Graphium sp*. F1B4 that uses 1,2-dioxygenase (Santos et al., 2003). Similar properties reveals *Fusarium sp* FE11 that is able to mineralize hydroxybenzenes (Santos and Linardi, 2004). Leontievsky and co-workers reported degradation of 2,4,6-trichlorophenol to 2,6-dichloro-1,4-hydroquinole and 2,6-dichloro-1,4-benzoquinone by *Panus tigrinus* that produces para-diphenol oxidase (Leontievsky et al., 2000).

Algas

Numerous researches reported that alga are capable to transform many xenobiotics including phenols. Modification of xenobiotics structure by eucaryotic organisms affects on the increase of susceptibility of the compound to bacteria “attack” in a hydroxylation process (Semple et al., 1999). The representative of alga is *Ochromonas danica* CCAP 933/28 growing photoheterotrophicaly and heterotrophicaly on p-cresol and phenol that is mineralized in this procces (Semple, 1997). *Ochromonas danica* also degrades some isomers of methylphenols to methylcatechols (xylenols) (Semple and Cain, 1997). *Chlorella fusca* reveals capacity to degrade 2,4-dichlorophenol (Tsuji et al., 2003). *C. fusca* and *Anabaena variabilis* in photoautotrophic conditions degrade some chlorophe-nols, 2-nitrophenol and 3-nitrophenol (Hirooka et al., 2003). *Coenochloris pyrenoidosa* and *Chlorella vulgaris* are able to degrade 4-nitrophenol during 3 days (Lima et al., 2003) and p-chlorophenol in a concentration of 150 mg/L in 5 days (Lima et al., 2004). Another species - *Prototheca zopifii* degrades numerous hydrocarbons contained in fuel and driving oil (Semple et al., 1998). Transformation of phenols is also performed by diatoma *Skeletonema costatum*

that degrades 2,4-dichlorophenol with high effectivity (Yang et al., 2002). Algae are also capable to degrade high concentrations of phenols. For example *Ankistro-desmus braunii* and *Scenodesmus quadricauda* degraded phenol in a concentration of 400 mg/L (Pinto et al., 2002).

Plants

The ability of degradation of xenobiotics by plants – phytoremediation is used to remove these compounds from environment. Plants have many peroxidases that are mainly responsible for transformation of toxic compounds. In *Vaccinium myrtillus* high activity of peroxidases leaded to degradation of 2,4,6-trichloro-phenol with 96% effectivity (Stazi et al., 2001). In another experiment cultures of carrot roots (*Dacus carota* L.) transformed phenol with high effectivity (90%) within 120 hours of incubation (de Araujs et al., 2002). Agostini and co-workers employed cultures of *Brassica napus* to eliminate high concentration (100 – 1000 mg/L) of 2,4-dichlorophenol. In a wide range of pH values (from 3 to 8) and presence of hydrogen peroxide the compound was mineralized with high effectivity of 97% to 99% within 1 hour (Agostini et al., 2003). Root systems play an important role in degradation of persistent and very toxic xenobiotics. In an experiment cometabolism of *Agropyron cristatum* and *Agropyron desertosum* and different bacterial cultures leaded to mineralization of penta-chlorophenol. Root systems provided nutrients which increased development of bacteria that degraded PCP with high effectivity (Miller and Dyer, 2000). Cometa-bolism of pentachlorophenol present in soil was also observed in cultures of *Pseudomonas gladioli* M-2196 and roots of Chinese chive (*Allium tuberosum)* (Nakamura et al., 2004).

Metabolism of phenols in vertebrates

Numerous researches concerning metabolism of organic compounds including phenols in vertebrates has been performed. It was reported that toxins which penetrate organism and those synthesised in organism undergo similar metabolic processes. The investiga-tion performed on fish revealed that phenols are conjugated with glucuronic and also are bound with sulphates (Layiwola et al., 1983; Nagel and Urich, 1983; Haritos et al., 1995; Oikari and Kunnamo-Ojala, 1987). Similar processes were observed in reptiles and mammals (Oddy et al., 1997; Bruce et al., 1987). Phe-nols in living organisms are also bound with phos-phates and aminoacids (Nagel and Urich, 1983). It was also reported that conjugation mainly proceeds in cytosol of liver and is catalyzed by microsomal enzy-mes – monooxygenases (Oddy et al., 1997). Sulpha-tion is catalyzed by a group of cytosolic sulphotrans-ferases (Tamura et al., 1997) that use a substrat – 5'-phosphotiosulphate-3'phosphoadenosine as donor that binds both xenobiotics and endogenous compounds (Coughtrie, 1996) glucuronidation employes uridino -5'-glucuronid acid.

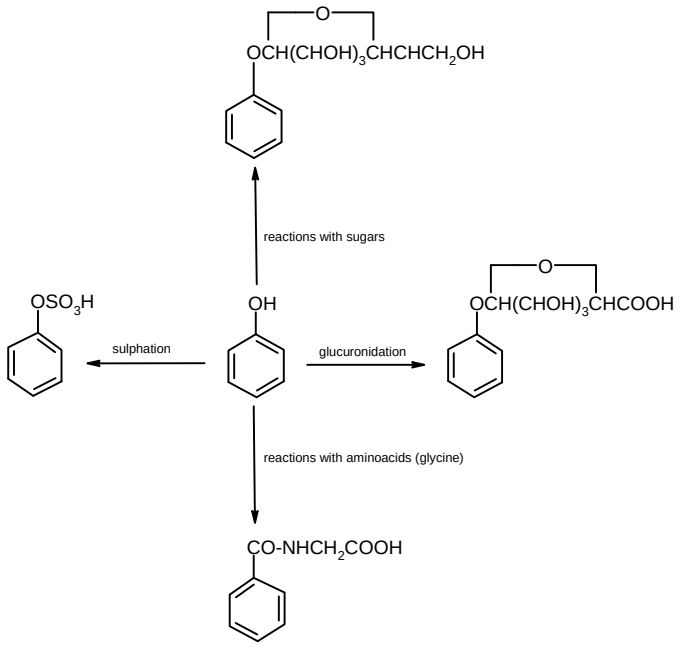

Fig. 4. Transformations of phenol in vertebrates.

Other investigations revealed that phenols in low concentrations are mainly sulphated and higher concentration of substrate induces mainly glucuro-nidation process. Phenols are usually oxidized before conjugation what was observed in an experiment on fish in which quinol glucuronide and quinol sulphate were determined (Beyer and Frank, 1985). The discussing processes lead to detoxication of phenols (and other xenobiotics) as the complexes are better soluble in plasma and are excreted with highest effectivity. Some toxic phenols are formed in living organism from non-toxic compounds. In digestive tract phenol and p-cresol are formed from tyrosine at the participation of *Citrobacter freundi* (Hiraku et al., 1998).

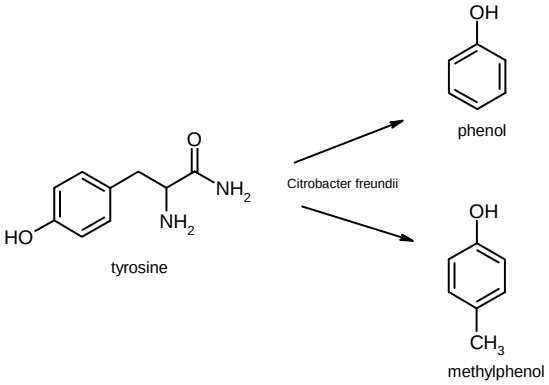

Fig. 5. Transformation of tyrosine to phenol and methyl-phenol.

Para-aminophenol formation proceeds when aniline and hydrogen peroxide are catalyzed by microsomal peroxidase 8 (Osman et al., 1996) and amino and nitrophenols are formed due to transformation of dinitro derivatives (Nikonorow, 1979). Above mentioned peroxidase is also capable to nitrate phenol in the presence of hydrogen peroxide and nitrogen peroxide to yield 4-nitrophenol (Ricoux et al., 2001). Toluene transformation leads to formation of ortho and para-cresol and anisole is formed during O-methylation of phenol (investigations performed on rats) (Takahara et al., 1986).

Enzymes that participate in phenols transformations

Phenol and its methylated derivatives are hydroxyla-ted to respective catechols by phenol hydroxylase [EC. 1.10.3.1] (Powlowski et al., 1996; Oian et al., 1997). Similar process is leaded by lactate oxidase [EC. 1.1.3.2.] at the participation of hydrogen pero-xide (Monzani et al., 1997). Catechol tyrosinase due to its cresolic activity oxidizes phenols to respective catechols. Phenols transformation to respective quinones appears at the participation of diphenol oxidase [EC. 1.13.1.1.] Transformation of phenols to catechols is also catalyzed by phenol 4-hydroxylase that is produced by *Trichosporon cutaneum*. Oxygenases [EC. 1.13.1.1.] are important group of enzymes that catalyze oxidative cleavage of aromatic compounds including phenols, catechols and trihydroxylated aromatic alcohols (Powlowski et al., 1997). Several of above mentioned compounds are enzymatically clea-vaged by dioxygenases between first and second carbon atoms (intradiol cleavage) and between second and third position (extradiol cleavage) (Ito and Que, 1997). As the result of described processes phenol, catechol, 4-chlorophenol, 4-fluorophenol and 4-methylphenol are degraded to muconolactones and then mineralized (Sauret-Ignazi et al., 1996). *Pseudomonas sp*. S-47 produces catechol 2,3-dioxygenase that converts 4-chlorocatechol and catechol in meta position to form 5-chloro-2-hydroxymuconic semialdehyde and 2-hydroxymuconic aldehyde respectively (Noh et al., 2000). Hydroquinol (1,2,4-trihydroxybenzene) is cleavaged to maleiloacetate by hydroquinol 1,2-dioxygenase. High affinity towards chlorinated phenols and especially chlorocatechols also reveal chlorocatechol dioxygenases (Maltseva et al., 1994). The important group of enzymes are monooxygenases. The example is 2,4,6-trichlorophenol-4-monooxygenase that transforms 2,4,6-trichlorophenol to 2,6-dichlorophenol (Wieser et al., 1997). Pentachlorophenol monooxygenase [E.C. 1.14.13.50] participates in dechlorination of catechols (Noh et al., 2000), the enzyme also converts tetrachlorohydroquinone and trichlorohydroquinone and catalyzes isomerisation of maleiloacetate to form inorganic compounds (Anandarajah et al., 2000). The another example is tetrachlorohydroquinone dehalogenase produces by *Sphingomonas chlorophenolica* that catalyses reductive dechlorination of tetrachlorohydroquinone and trichlorohydroquinone during pentachlorophenol transformation reaction (Kiefer et al., 2002). Elimination of nitro groups from ortho-nitrophenol and paranitrophenol proceeds at the participation of monophenol monooxygenase (Haigler et al., 1996) and demethylation of methylcatechols (in mammalian cells) proceeds at presence of catechol O-methytransferase [EC. 2.1.1.6] (Ovaska and Ylinieme-la, 1998).

ABIOTIC TRANSFORMATION OF PHENOLS

Minerals present in the environment playing an impor-tant role degradation of organic matter and xenobio-tics, as they are capable to oxidate and reduce numerous compounds. Essential effect on organics transfor-mation exerts also photochemical transformation. Manganese oxides catalyze trans-formation of phenols and their derivatives. In an experiment performed *in vitro* in acidic conditions catechol was oxidized by birnesite (MnO_2). As carbon dioxide was detected in a reaction it was stated that xenobiotic was partly mineralized in this process. Rest of catechol was converted to polymer that was stable and non-toxic product of the reaction (Majcher et al., 2000). It was also reported that catechol may be oxidized by other manganese oxides in which the metal has third and fourth oxidation degrees (Matocha et al., 2001). The another experiment showed that ferrihydrite that has the third oxidation degree is capable to mineralize catechol, hydroquinone and guaiacol (Pracht et al., 2001). The another mineral that is able to oxidate phenolic xenobiotics is hydrated iron oxide (goethite) that at the participation of hydrogen peroxide transforms 2-chlorophenol (Lu et al., 2002). Lin and co-workers in an experiment reported adsorption and effective degradation of phenol by hydratated silica oxides – bentonites (Lin et al., 2000). In environmental transforma-tions an essential role play reactions induced by UV irradiation. It was showed that pentachloro-phenol photoreduction leaded to formation of 2-de-hydro-2,3,4,5,6-pentachlorocyclohexane and 2,3, 4,5,6-pentachlorocyclohexanone (Ray et al., 2002). The conversion of phenols to catechols under UV irradiation was also described by Różański (Różański, 1998).

REFERENCES

Agostini E., Coniglio M., Milard S., Tigier H. & Giulietti A. (2003). Phytoremediation of 2,4-di-chlorophenol by *Brassica napus* hairy root cultures. Biotechnol. Appl. Biochem. **37**, 139-144.

Anandarajah K., Kiefer P., Donohoe B. & Copley S. (2000). Recruitment of a double bond isomerase to serve as a reductive dehalogenase during biodegradation of pentachlorophenol. *Biochem*. **39**, 5303-5311.

Andretta C., Rosa R., Tondo E., Gaylarde C. & Henriques J. (2004). Identification and molecular characterization of a *Bacillus subtilis* IS 13 strain involved in the biodegradation of 4,5,6-trichloroguaiacol. *Chemosphere*. **55**, 631-639.

Aneez A., Kunhi A. (1999). Degradation of high concentrations of cresols by Pseudomonas. *World J. Microbiol. Biotechnol*. **15**, 281-283.

Aranda C., Godoy F., Becerra J., Barra R. & Martinez M. (2003). Aerobic secondary utilization of non-growth and inhibitory substrate 2,4,6-trichlorophenol by Sphingopyxis chilensis S37 and Sphingopyxis-like strain S32. *Biodegrad*. **14**, 265-274.

deAraujs B., Charlwood B. & Pletsch M. (2002). Tolerance and phenol and chloroderivatives by hairy root of Dacus carota L. *Environ. Pollut*. **117**, 329-335.

Bastos A., Tornisielo L., Nozawa R., Trevors T. & Rossi A. (2000). Phenol metabolism by two microorganisms isolated from Amazonian forest soil samples. *J. Microbiol. Biotechnol*. **24**, 403-409.

Becker P., Wand H., Martius G., Weiβbrodt E. & Stottmeiser U. (1998). Functional and structural successions in arbitrary samples of heterotrophic bacteria during aerobic treatment of lignite - carbonization wastewater in *in situ* enclosures. *Can. J. Microbiol*. **44**, 211-220.

Beyer J. & Frank G. (1985). Hydroksylation and conjugation of phenol by the frog *(Rana temporaria*). *Xenobiot*. **15**, 277-280.

Beyersdorf-Radeck B., Riedel K., Karlson U., Bachmann T. & Schmid R. (1998). Screening of xenobiotic compounds degrading microorganisms using biosensor techniques. *Microbiol. Res*. **153**, 239-245.

Boháčová V., Godocikova J. & Polek B. (2001). Biodegradation of phenol substances by pure and mixed culture. *Biol*. **56**, 263-269.

Bondar V., Boersma M., Van Berkel W., Finkelstein Z., Golovlev E., Baskunow B., Vervoot J., Golovleva L. & Rietjens I. (1991). Preferential oxidative dehalogrnation upon cornversion of 2-halophenols by *Rhodococcus opacus* 1G. *FEMS Microbiol. Let*. **181**, 73-82.

Bruce R., Santodonato J. & Neal M. (1987). Summary review of the health effects associated with phenol. *Toxicol. Indust. Health*. **3**, 535-568.

Cho N., Nam H., Park J., Koo C., Lee S., Pashenova N., Ohga S & Leonowicz A. (2001). Transformation of chlorophenols by white-rot fungi and their laccase. *Holzforsch*. **55**, 579-584.

Clauβen M. & Schmidt S. (1998). Biodegradation of phenol and p-cresol by the hypomycete *Scedosporium cepiospermum*. *Res. Microbiol*. **149**, 399-406.

Cort T. & Bielefeldt A. (2000). Effects of Surfactants and Temperature on PCP Biodegradation. *J. Environ. Engineer*. **22**, 635-643.

Coughtrie M. (1996). Sulphation catalyzed by the human cytosolic sulphotransferases - chemical defence or molecular terrorism? *Human Experim. Toxicol*. **15**, 547-555.

Dai M., Rogers J., Warner J. Copley S. (2003). A previously unrecognized step in pentachlorophe-nol degradation in Sphingobium chloropheno-licum is catalased by tetrachlorobenzoquinone reductase (PcpD). *J. Bacteriol*. **185**, 302-310.

Drijhout F., Fraaije M., Jorsgejan H., van Berkel W. & Franssen M. (1988). Enantoselective hydroxylation of 4-alkylophenols by vanillyl alcohol oxidase. *Biotechnol. Bioeng*. **59**, 171-177.

Duffner F. M., Müller R., (1998). A novel phenol hydroksylase and catechol 2,3-dioksygenase from the termophilic *Bacillus thermoleovorans strain A2*

nucleotide sequence and analysis of the genes. *FEMS Microbiol. Let*. **161**, 47-45.

Erhan E., Yer E., Akay G., Kesinkler B. & Kesinkler D. (2004). Phenol degradation in a fixed-bed bioreactor using micro-cellular polymer-immobilized *Pseudomonas syringae*. J. *Chem. Technol. Biotechnol*. **79**, 195-206.

Fialova A., Boschke E. & Bley T. (2004). Rapid monitoring of the biodegradation of phenol-like compounds by the yeast *Candida maltosa* using BOD measurements. *Inter. Biodeterior. Biodegradation*. **54**, 69-76.

Finkelstein Z., Baskunov B., Boersma M., Vervoort J., Golovlev E., van Berkel W., Golovleva L. & Rietjens I. (2000). Identification of Fluoropyrogallols as New Intermediates in Biotransformation of Monofluorophenols in *Rhodococcus opacus* 1 cp. *Appl. Environ. Microbiol*. **66**, 2148-2153.

Golovleva L., Zaborina O., Pertsowa R., Baskunov B., Schurukhin Y. & Kuzmin S. (1992). Degradation of polychlorinated phenols by *Streptomyces rochei* 303. *Biodegrad*. **2**, 201-208.

Grey R. Höfer Ch. & Schlosser D. (1998). Degradation of 2-chlorophenol and formation of 2-chloro-1,4-benzoquinone by mycelia and cell-free crude culture liquids of *Trametes versicolor* in relation to extracellular laccase activity. *J. Basic Microbiol*. **38**, 371-382.

Haigler B., Suen W. & Spain J. (1996). Purification and sequence analysis of 4-methyl-5-nitrocatechol oxygenase from *Burkholderia sp*, Strain DNT. *J. Bacteriol*. **178**, 6019-6024.

Hammer E., Kneifel H, Hofmann K. & Schauer F. (1996). Enhanced excretion of intermediates of aromatic amino acid catabolism during chloro-phenol degradation due to nutrient limitation in the yeast *Candida maltosa*. *J. Basic Microbiol*., **36**, 239-243.

Haritos V., Brumley C., Holdway D. & Ahokas J. (1995). Metabolities of 2-chlorosyringaldehyde in fish bile: indicator of exposure to bleached hardwood effluent. *Xenobiot*. **25**, 963-971.

Häggblom M. (1998). Reductive dechlorination of halogenated phenols by a sulphate-reducing consortium. *FEMS Microbiol. Ecol*. **26**, 35-41.

Häggblom M., Nohynek L., Palleroni J., Kronqvist K., Nurmiaho-Lassila E., Salkinoja-Salonen M., Klatte S. & Kroppenstedt R. (1994). Transfer of polychlorophenol-degrading *Rhodococcus chlorophenolicus* to the genus *Mycobacterium* as *Mycobacterium chlorophenolicum sp.* nov. *Int. J. Syst. Bacteriol*. **44**, 485-493.

He Q. & Sanford R. (2002). Induction characteris-tics of reductive dehalogenation in the ortho-halophenolrespiring bacterium, *Anaeromyxo-bacter dehalogenans. Biodegradation.* **13**, 307-316.

Heiss G., Trachtman N., Abe Y., Takeo M. & Knackmuss H. (2003). Homologous npdGI genes in 2,4-dinitrophenol- and 4-nitrophenoldegrading *Rhodococcus spp*. *Appl. Environ. Microbiol*. **69**, 2748-2754.

Hinteregger Ch., Leitner R., Loidl M., Fersch A. & Streichsbier F. (1992). Degradation of phenol and phenolic compounds by *Pseudomonas putida EKII*. *Appl. Microbiol. Biotechnol.* **37**, 252-259.

Hinteregger C. & Streichsbier F. (1997). *Halomo-nas sp*., a moderately halophilic strain, for biotreatment of Saline phenolic wastewater. *Biotechnol. Let*. **19**, 1099-1102.

Hiraku Y. Yamasaki M. & Kawanishi S. (1998). Oxidative DNA damage induced by homoge-ntistic acid, a tyrosine metabolite. *FEBS Let*. **432**, 13-16.

Hirooka T., Akiyama Y., Tsuji N., Nakamura T., Nagase H., Hirata K. & Miyamoto K. (2003). Removal of hazardous phenols by microalgae under photoautotrophic conditions. *J. Biosci. Bioengin*. **95**, 200-203.

Hofmann K., Knackmuss H. & Heiss G. (2004). Nitrite elimination and hydrolytic ring cleavage in 2,4,5-trichlorophenol (Picric acid) degradation. *Appl. Environ. Microbiol*. **70**, 2854-2860.

Hofrichter M. Bublitz F. & Fritsche W. (1995). Cometabolic degradation of o-cresol and 2,6-dimethylphenol by *Penicillum frequentas Bi 7/2*. *J. Basic Microbiol*. **35**, 303-313.

Im W., Bae H., Yokota A. & Lee S. (2004). *Herbaspirillum chlorophenolicum sp*. nov., a 4-chlorophenol-degrading bacterium. *Int. J. Syst. Evolution. Microbiol*. **54**, 851-855.

Ingerslev F. & Nyholm N. (2000). Shake – Flask Test for Determination of Biodegradation Rates of C – Labeled Chemical at Low Concentrations in Surface Water Systems. *Ecotoxicol. Environ. Safety*. **45**, 274-283.

Ito M. & Que L. (1997). Biomimetric extradiol cleavage of catechols insight into enzyme mechanism. Angew. *Chem. Int. Ed. Engl*. **36**, 1342-1344.

Jagoe Ch., Kreifels S. & Li Jongming. (1997). Covalent binding of catechols to SCR family SH 2 domains. *Bioorg. Medic. Chem. Let*. **7**, 113-116.

Jeong J., Kim J., Kim C., Hwang I. & Lee K. (2003). 3- and 4-alkylphenol degradation pathway in *Pseudomonas sp.* strain KL28: genetic organization of the lap gene cluster and substrate specificities of phenol hydroxylase and catechol 2,3-dioksygenase. *Microbiol*. **149**, 3265-3277.

Johnson G., Jain R. & Spain J. (2000). Properties of the trihydroxytoluene oxygenase from *Burkholderia cepacia* R34: an extradiol dioxygenase from the 2,4-dinitrotoluene pathway, *Arch. Microbiol*. **173**, 86-90.

Juteau P., Beaudet R., McSween G., Lepine F., Milot S. & Bisaillon J. (1995). Anaerobic biodegradation of pentachlorophenol by a methanogenic consortium. *Appl. Microbiol. Biotechnol*. **44**, 218-224.

Kao C., Chai C., Liu J., Yeh T., Chen K. & Chen S. (2004). Evaluation of natural and enhanced PCP biodegradation at a former pesticide manufacturing plant. *Water. Res*. **38**, 663-672.

Kahl M., Makynen E., Kosian P. A., Ankley G. (1997). Toxicity of 4-nonylophenol in a life - cycle test with the midge *Chironomus tetanus*. *Ecotoxicol. Environ. Saf*. **38**, 155-160

Kazumi J., Häggblom M., Young L. (1995). Degradation of monochlorinated and nonchlo-rinated aromatic compounds under iron-reducing conditions. *Appl. Environ. Microbiol*. **61**, 4069-4073.

Kitagawa W., Kimra N. & Kamagata Y. (2004). A novel degradation gene cluster from a gram-positive

bacterium, *Rhodococcus opacus* SAO101. *J. Bacteriol*. **186**, 4894-4902.

Knuutinen J. (1982). Analysis of chlorinated quaiacols in spent bleach liquor from a pulp mill. *J. Chromat*. **248**, 289-295.

Kowalska M., Bodzek M. & Bochdziewicz J. (1998). Biodegradation of phenols and cyjanides using membranes with immobilized microorga-nisms. *Proc. Biochem*. **33**, 189-197.

Laine M. & Jorgensen K. (1996). Straw compost and bioremediated soil as inoculate for the bioremedation of chlorophenol - contaminated soil. *Appl. Environ. Microbiol*. **44**, 1507-1513.

Law W., Lau W., Lo K., Wai L. & Chiu S. (2003). Removal of biocide pentachlorophenolin water system by spent mushroom compost of *Pleurotus pulmonaris. Chemosphere*. **52**, 1531-1537.

Layiwola P., Linnecar D. & Knights B. (1983). The biotransformation of three ^{14}C-labelled phenolic compounds in twelve species of freshwater fish. *Xenobiot*. **13**, 107-113.

Leontievsky A., Myasoedova N., Baskunov B., Evans C. & Golovleva L. (2000). Transformation of 2,4,6-trichlorophenol by the white rot fungi *Panus tigrinus* and *Coriolus versicolor*. *Biodegrad*. **11**, 331-340.

Leung K., So J., Kostrzycka M., Lee H. & Trevors T. (2000). Using a green fluorescent protein gene – labeled p-nitrophenol – degradaing Moxarella strain to examine the protrctive effect of alginate encapsulation against protozoan grazing. *J. Microbiol. Methods*. **39**, 205-211.

Li T., Bisaillon J., Villemur R., Letourneau L., Bernard K., Lepine F. & Beaudet R. (1996). Isolation and characterization of a new bacterium carboxylating phenol to benzoic acid under anaerobic conditions. *J. Bacteriol*. **178**, 2551-2558.

Lima S., Raposo M., Castro P. & Morais R. (2004). Biodegradation of p-chlorophenol by microalgae consortium. *Water Res*. **38**, 97-102.

Lima S., Castro P. & Morais R. (2003). Biodegra-dation of p-nitrophenol by microalgae. *J. Appl. Physiol*. **15**, 137-142.

Lin S., Huang C. & Cheng M. (2002). Optimiza-tion of multistage phenol adsorption by organo-bentonites: theorethical developments and experimental verification. *Environ. Technol*. **23**, 609-622.

Lu M., Chen J. & Huang H. (2002). Role of goethite dissolution in the oxidation of 2-chlorophenol with hydrogen peroxide. *Chemosphere*. **46**, 131-136.

Majcher E., Chorover J., Bollag J. & Huang P. (2000). Evolution of CO_2 during Birnessite-Induced Oxidation of ^{14}C-Labelled Catechol. *Soil Sci. Soc. Am. J*. **64**, 157-163.

Maltseva O., Solyamkowa I. & Golovleva A. (1994). Chlorokatechol 1,2-dioxygenase from Rhodococcus erythropolis 1 CP. *Europ. J. Chrom*. **226**, 1053-1061.

Matocha Ch., Sparks D., Amonette J. & Kukkadapu R. (2001). Kinetics and Mechanism of Birnessite Reduction by Catechol. *Soil Sci. Soc*. **65**, 58-66.

McGrath R., Singleton I. (2000). Pentachloro-phenol transformation in soil: a toxicological assessment. *Soil Biol. Biochem*. **32**, 1311-1314.

Miller E. & Dyer W. (2002). Phytoremediation of pentachlorophenol in the crested wheatgrass *(Agropyron cristatum x desertorum)* rhizosphere. *Inter. J. Phytoremed*. **4**, 223-238.

Milo R., Duffner F., Bauer M. & Mueller R. (1997). Degradation of phenol by thermophilic *Bacillus* species, purification and characteriza-tion of catechol 2,3-dioksygenase. In: 8th Europe-an Congress on Biotechnology Book of Abs-tracts. *Hung. Biochem. Soc*. **8**, 39.

Mirano T., Monda Y., Watanabe T. & Kuwhara M. (2000). Degradation of Bisphenol A by the Lignin-Degrading Enzyme, Manganase Peroxidase Produced by the White-rot Basidiomycete, *Pleurotus ostreatus*. *Biosci. Biotechnol. Biochem*. **64**, 1958-1962.

Moiseva O., Solyamikowa J., Kaschabek S. Groning J., Thiel M., Golovleva L. & Schomann M. (2002). A New Modified ortho Cleavage Pathway of 3-Chlorocatechol Degradation by Rhodococcus opacus 1CP: Gen. Biochem. *Evid. J. Biotechnol*. **184**, 5282-5292.

Monzani E., Gatti A. L., Profumo A., Casella L. & Gullotti M. (1997). Oxidation of phenolic compounds by lactoperoxidase, Evidence for presence of a low-potential compound II during catalytic turnover. *Biochem*. **7**, 1918-1926.

Nagel R. & Urich K. (1981). Quinol sulphate, a new conjugate of phenol in goldfish. *Xenobiot*. **13**, 97-100.

Nakamura T., Motoyama T., Suzuku Y., Yamaguchi. (2004). Biotransformation of pentachlorophenol by Chinese chive and recombinant derivative of its rhizosphere-complemement microorganism, *Pseudomonas gladioli* M-2196. *Soil Biol. Biochem*. **36**, 787-795.

Nam IH., Chang YS., Hong HB. & Lee YE. (2003). A novel catabolic activity of Pseudo-monas veronii in biotransformation of penta-chlorophenol. *Appl. Microbiol. Biotechnol*. **62**, 284-290.

Nga D., Attenbuchner J. & Heiss G. (2004). NpdR, a represor involved in 2,4,6-trinitrophenol degradation in Rhodococcus opacud HL PM-1. *J. Bacteriol*. **186**, 98-103.

Nikonorow M. Toksykologia żywności. Państwo-wy Instytut Wydawnictw Lekarskich. 1979. Warszawa.

Noh S., Kim Y., Min K., Karegoudar T. & Kim Ch. (2000). Cloning and Nucleotide Sequence Analysis of *xylE* Gene Responsible for *meta*-Cleavage of 4-Chlorocatechol from *Pseudomonas* sp. S-47. *Molec. Cells*. **10**, 475-479.

Nohynek L., (1995). Description of four penta-chlorophenol - degrading bacterial strains as *Sphingomonas chlorophenolica sp. now*. *Sys. Appl. Microbiol*. **18**, 527-538.

Oddy E., Manchee G. & Coughtrie M. (1997). Assesment of rat liver slices as a suitable model system for studing the simultaneous sulphation and glucuronidation of phenolic xenobiotics. *Xenobiot*. **27**, 369-377.

Oian H., Edlung U., Powlowski J., Shingler V. & Sethson I. (1997). Solution structure of phenol hydroksylase protein component P2 determined by NMR spectroscopy. *Biochem*. **73**, 495-504.

Oikari A. & Kunnamo-Ojala T. (1987). Tracing of xenobiotic contamination in water with the aid of fish bile metabolities: a field study with caged *Rainbow trout* (Salmo gairdneri). *Aquat. Toxicol*. **9**, 327-341.

Okeke B., Paterson A., Smith J. & Watson-Craik I. (1997). Comparative biotransformation of pentachlorophenol in soils by solid substrate cultures of *Lentinula edodes. Appl. Microbiol. Biotechnol*. **48**, 563-569.

Osman A., Koerts J., Boersma M., Boernen S., Veeger C. & Rietjens I. (1996). Micropero-xidase/H_2O_2 - catalyzed aromatic hydroxylation proceeds by a cytochrome-P-450-type oxygen - transfer reaction mechanism. *Europ. J. Biochem*. **240**, 232-238.

Ovaska M. & Yliniemelä A. (1998). A semiempirical study on inhibition of catechol O-methyltransferase by substituted catechols, *J. Comp-Aid. Mol. Design*. **12**, 301-307.

Padilla L., Matus V., Zenteno P. & Gonzalez B. (2000). Degradation of 2,4,6-trichlorophenol via chlorohydroxyquinol in *Ralstonia eutropha* JMP134 and JMP 222. *J. Basic Microbiol*. **40**, 243-249.

Perron N. & Welander U. (2004). Degradation of phenol and cresols at low temperatures using a suspended-carrier biofilm process. *Chemosphere*. **55**, 45-50.

Pinto G., Pollio A., Previtera L. & Temussi F. (2002). Biodegradation of phenols by micro-algae. *Biotechnol. Let*. **24**, 2047-2051.

Powlowski J., Sealy J., Shingler V. & Cadieux E. (1996). On the role of Dmpk, an auxiliary protein associated with multicomponent phenol hydroksylase from *Pseudomonas sp. strain CF600*. *J. Biol. Chem*. **272**, 945-951.

Pracht J., Boenigk J., Isenbeck-Schroter M., Keppler F. & Scholer M. (2001). Abiotic Fe(III) induced mineralization of phenolic substances. *Chemosphere*. **44**, 613-619.

Ray R., Singh S., Hans R. & Joshi P. (2002). Identification of new photoreduction products of entachlorophenol. *J. Environ. Monit*. **4**, 449-451.

Reddy G. & Gold M. (2000). Degradation of pentachlorophenol by Phanerochaete Chryso-sporium – intermediates and reactions inrolved. *Microbiol*. **146**, 405-413.

Ricoux R., Boucher J., Mansuy D. & Mahy J. (2001). Microperoxidase 8 catalyzed nitration of phenol by nitrogen dioxide radicals. *Eur. J. Biochem*. **268**, 3783-3788.

Różański L., (1998). Przemiany pestycydów w organizmach żywych i środowisku, Agra-Enviro Lab. Poznań.

Rutgers M., Gooch D., Breure A. & Van Andel J. (1996). Assesment of inhibition kinetics of the growth of strain P5 on pentachlorofenol under steady-state conditions in a nutristat. *Arch. Microbiol*. **165**, 194-200.

Santos V. & Linardi V. (2004). Biodegradation of phenol by filamentous fungi isolated from industrial effluents – identification and degra-dation potential. *Process Biochem*. **39**, 1001-1006.

Santos V., Helibuth N., Braga D., Monteiro A. & Linardi V. (2003). Phenol degradation by *Graphium sp*. FIB4 isolated from industrial effluents. *J. Basic Microbiol*. **43**, 238-248.

Santos V. & Linardi V. (2001). Phenol degradation by yeasts isolated from industrial effluents. *J. Gen. Appl. Microbiol*. **44**, 213-221.

Saraswat N., Alleman J. & Smith T. (1994). Enzyme immunoassay detection of *Nitrosomonas europaea*. *Appl. Environ. Microbiol*. **60**, 1969-1973.

Sauret-Ignazi G., Gagnon J., Beguin C., Barrelle M., Markowicz Y. & Pelmont J. (1996). Characterization of a chromosomally encoded catechol 1,2-dioksygenase [E.C. 1.13.11.1.] from *Alicagenes eutrophus CH34*. *Arch. Microbiol*. **166**, 42-50.

Schirmer F., Ehrt S. & Hillen. (1997). Expression, inducer spectrum, domain structure, and function of MopR, the regulator of phenol degradation in *Acinetobacter calcoaceticus NCIB8250*. *J. Bacteriol*. **179**, 1329-1336.

Schlosser A., Grey R., Hofer Ch. & Fahr K. Degradation of Chlorophenols by Basidiomycetes [in:] Bioremediation of contaminated soils. Edit. Wise L. & Trandto J. 2000. New York · Basel.

Schröder M., Müller C., Posten C., Deckwer W. & Hecht V. (1997). Inhibition kinetics of phenol degradation from unstable steady-state data. *Biotechnol. Bioeng*. **54**, 567-576.

Semple K, Ronald C & Schmidt S. (1999). Bidegradation of aromatic compounds by microalgae. *FEMS Microbiol. Let*. **170**, 291-300.

Semple K. (1997). Biodegradation of phenols by a eukaryotic alga. Res. Microbiol., **148**, 365-367.

Semple K. & Cain R. (1997). Degradation of phenol and its methylated homologues by *Ochromonas danica*. *Microbiol. Let*. **152**, 133-139.

Shaw L., Beaton Y., Glover L., Killham K. & Meharg A. (1999). Development and characterization of a lux-modified 2,4-dichlorophenol – degrading *Burkholderia sp*. RASC. *Environ. Microbiol*. **1**, 393-399.

Sleeger B. & Stanier R. (1950). The bacterial oxidation of aromatic compounds. *J. Biol. Chem*. **158**, 525-530.

Soares A., Guieysse B. & Mattiason B. (2003). Biodegradation of nonylphenol in a continuous packed-bed bioreactor. *Biotechnol. Let*. **25**, 927-933.

Stazi S., Annibale A. & Sermanni G. (2002). Kinetic behaviour and degradative capability of *Lentinula edodes* laccase isoenzymes with differently substituted chlorinated substrates. *Fresenius Environ. Bull*. **11**, 583-588.

Stazi S., Feveiro P., Sermanni G. & Barros R. (2001). Oxidative polymerization and partial dechlorination of 2,4,6-trichlorophenol by mixture of peroxidase isoenzymes from *Vaccinium myrtillus*. *J. Chem. Technol. Biotechnol*. **76**, 210-214.

Steinle P., Thalmann P., Höhener P., Hanselmann K. & Stucki G. (2000). Effect of Environmental Factors on the Degradation of 2,6-Dichlorophe-nol in Soil. *Environ. Sci. Technol*. **34**, 771-775.

Swarts M., Verhagen F., Field J. & Wijnberg J. (1998). Trichlorinated phenols from *Hypholoma elongatum*. *Phytochem*. **49**, 203-206.

Tabak H. & Chambers C. (1964). Phytochemistry. *Anal. Biochem*. **95**, 351-358.

Takahara E., Ohta S. & Hirobe M. (1986). Effect of oxygen concentration on the metabolic pathway of anisole in rat liver microsomes. *Biochem. Pharmacol*. **35**, 541-544.

Takeo M., Yasukawa T., Abe Y., Niihara S., Maeda Y. & Negoro S. (2003). Cloningand characterization of a

4-nitrophenol hydroxylase gene cluster from *Rhodococcus sp*. PN1. *J. Biosci. Bioeng*. **95**, 139-145.

Tamura H., Miyawaki A., Inoh N., Harada Y., Mikoshiba K. & Matsui M. (1997). High sulfotransferase activity for phenolic aromatic odorants present in the mouse olfactory organ. *Chem-Biol*. *Interact*. **104**, 1-9.

Tsuji N., Hirooka T., Nagase H., Hirata K. & Miyamoto K. (2003). Photosynthesis-dependent removal of 2,4 dichlorophenol by *Chlorella fusca* var. vacuolata. Biotechnol. Let. **25**, 241-244.

Ushiba Y., Takahara Y. & Otha H. *Sphingobium amiense sp*., nov. a novel nonylphenol degrading bacterium isolated from a river sediment. *Int. J. Syst. Evolut. Microbiol*. **53**, 2045-2048.

Valenzuela J., Bumann U., Cespedes R., Padilla L. & Gonzalez B. (1997). Degradation of Chlorophenols by *Alcaligenes eutrophus* JMP134 (pJP4) in Bleached Kraft Mill Effluent. *Appl. Environ. Microbiol*. **75**, 227-232.

Vroumsia T., Steiman R., Seigle-Murandi F. & Benoit-Guyod J. (1999). Effects of culture parameters on the degradation of 2,4-dichloro-phenoxyacetic acid (2,4-D) and 2,4-dichlorophe-nol (2,4-DCP) by selected fungi. *Chemosphere*. **39,** 1397-1405.

Wang Ch., Takenaka S., Murakami S & Aoki K. (2001). Isolation of benzoate utylizing *Pseudo-monas strain* from soil and production of catechol from benzoate by transpositional mutants. *Microbiol. Res*. **156**, 151-158.

Wang Ch. Lee Ch., Lu Ch. Chuang M. & Huang Ch. (2000). Biodegradation of 2,4,6-trichloro-phenol in the presence of primary substrate by immobilized pure culture bacteria. *Chemosphere*. **41**, 1873-1879.

Watanabe K. & Hino S. (1996). Identification of a functionally important population in phenol-digesting activated sludge with antisera raised against isolate bacterial strains. *Appl. Environ. Microbiol*. **62**, 3901-3904.

Watanabe K., Yamamoto S., Hino S. & Harayama S. (1998). Population dynamics of phenol-degrading bacteria in activated sludge determi-ned by gyro B - targeted quantitative PCR. *Appl. Environ. Microbiol*. **64**, 1203-1209.

Wieser M., Wagner B., Eberspächer J., (1997). Purification and characterization of 2,4,6-trichlorophenol-4-monooxygenase, a dehalo-genating enzyme from *Azotobacter sp*. Strain GP1. *J. Bacteriol.* **179**, 202-208.

Wurster M., Mundt S., Hammer E., Schauer F. & Lindequist U. (2003). Extracellular degradation of phenol by the cyanobacterium *Synechococcus* PCC 7002. J. Appl. Phycol. **15**, 171-176.

Yang S., Wu R. & Kong R. (2002). Biodegradation and enzymatic responses in the marine diatom *Skeletonema costatum* upon exposure to 2,4-dichlorophenol. *Aquat*. *Toxicol*. **59**, 191-200.

Zablotowicz R., Leung K., Alber T., Cassidy M., Trevors J., Lee H., Veldhuis L. & Hall J. (1999). Degradation of 2,4-dinitrophenol and selected nitroaromatic compounds by *Sphingomonas* sp. UG30. *Can. J. Microbiol*. **45**, 840-848.

Zeyer J., Kocher H. P., (1988). Purification and characterization of a bacterial nitrophenol oxygenase which converts ortho-nitrophenol to catechol and nitrite. *J. Bacteriol*. **170**, 1789-1794.