



HAL
open science

Effect of nonylphenol surfactants on fungi following the application of sewage sludge on agricultural soils

Albert Kollmann, A. Brault, Isabelle Touton, Jacqueline Dubroca, Véronique Chaplain, Christian Mougin

► **To cite this version:**

Albert Kollmann, A. Brault, Isabelle Touton, Jacqueline Dubroca, Véronique Chaplain, et al.. Effect of nonylphenol surfactants on fungi following the application of sewage sludge on agricultural soils. *Journal of Environmental Quality*, 2003, 32 (4), pp.1269-1276. hal-02677434

HAL Id: hal-02677434

<https://hal.inrae.fr/hal-02677434>

Submitted on 19 Jan 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - ShareAlike | 4.0 International License

1 Impact of nonylphenol surfactants on fungi following the application of sewage sludge on
2 agricultural soils

3

4

5

6 Albert Kollmann, Agathe Brault, Isabelle Touton, Jacqueline Dubroca, Véronique Chaplain
7 and Christian Mougin*

8

9

10 Unité de Phytopharmacie et Médiateurs Chimiques, Institut National de la Recherche
11 Agronomique, Route de Saint-Cyr, F-78026 Versailles Cedex

12

13

14

15 Abbreviation list:

16 NP, nonylphenol, mixture of isomers; 4NP, 4-*n*-nonylphenol; SA, sludge from Ambares;
17 SMF, spore multiplication factor; SP, sludge from Plaisir.

18

19

20

21

22

23 *corresponding author

24 Phone: 33-1-30-83-31-02

25 Fax: 33-1-30-83-31-19

26 Email: mougin@versailles.inra.fr

27

28

29

1 **Abstract**

2
3 The impact of nonylphenol on fungi following the application of contaminated sewage sludge
4 on agricultural soil was studied in laboratory experiments. Nonylphenol bioavailability and
5 adsorption were determined in the soil alone and soil/sludge mixtures. Mixing the soil with
6 sludge made it possible to measure the nonylphenol concentration in the soil solution
7 comprised between $6.6 \cdot 10^{-6}$ M and $3.8 \cdot 10^{-7}$ M according to the sludge. We then examined the
8 dose-response relationship between nonylphenol concentration in the culture medium and
9 both biomass production and germination rate of the spores from several strains of
10 filamentous fungi. When applied in this range of concentration, nonylphenol was without
11 noticeable short-term impact on these endpoints. Long-term exposure of fungi to nonylphenol
12 was also assessed. The most intensive effect was a strong stimulation of spore production and
13 germination in *Fusarium oxysporum*. Biomass production by the *Fusarium* strains also
14 increased. Finally, nonylphenol was shown to induce laccase production in *Trametes*
15 *versicolor*. We conclude that the potential of nonylphenol to adversely impact soil fungi
16 remains low.

17 18 **Introduction**

19
20 In many countries, application on cultivated land of sewage sludge produced from wastewater
21 treatment plants is common practice. New risks are emerging today for both the environment
22 and human health. Indeed, there may be adverse effects for micro-organisms and higher
23 plants, as well as for consumers (animals or humans) because of soil, water, feed and food
24 contamination (Bokern et al., 1998) by heavy metals, organic compounds and biological
25 agents.

26 Among organic chemicals, wastewater entering treatment plants contain nonylphenols (NP, a
27 mixture of branched isomers), an important compound in the production of many commercial
28 and industrial chemicals. NP is used to produce nonylphenol polyethoxylates, which are
29 nonionic surfactants widely used in domestic, agricultural and industrial applications.

30 NP is subsequently discharged into surface waters through the microbial biodegradation of
31 these polyethoxylates in sewage treatments (Ahel *et al.*, 1994a), and potential aquatic risks
32 have been extensively studied (for reviews see Sumpter, 1998; Servos, 1999; Nilsson, 2000;
33 Vos *et al.*, 2000). In this context, it is important to make a distinction between 4-*n*-NP (a main
34 compound present in the mixture of isomers) and NP (the mixture of isomers) because they

1 have some distinct physico-chemical properties. However, studies concerning the fate and
2 toxic effects of nonylphenol compounds refer in most cases to 4-*n*-NP alone. Both *in vitro* and
3 *in vivo* studies reported that this isomer is a potent endocrine disrupter, modulating
4 steroidogenesis and activity of hormone-metabolizing enzymes, and inducing feminization. It
5 binds onto cellular estrogenic receptors, thereby regulating the expression of estrogen-
6 responsive genes (Machala and Vondracek, 1998), and can cause proliferation of breast
7 cancer cells in women (Soto *et al.*, 1991).

8 However, most NP formed during wastewater treatment is associated with sludge, amounting
9 to 1 g or more *per* kg of dry sludge (Ahel and Giger, 1985; Ahel *et al.*, 1994a and b; APE
10 Research Council, 2002). NP is released onto terrestrial environments through sludge
11 application on agricultural land. Nevertheless, only little work has been done on the fate of
12 NP in soils (Topp and Starratt, 2000; Hesselsoe *et al.*, 2001, Dubroca *et al.*, 2003), and an
13 assessment of the potential risk has rarely been conducted (APE Research Council, 2002).
14 Yet, some studies revealed that NP can modify the structure of microbial communities of lake
15 sediments (Jontofsohn *et al.*, 2002). In the laboratory, production of carbon dioxide from soil
16 is inhibited by concentrations of NP higher than 100 mg/kg (APE Research Council, 2002),
17 which proved to be toxic to filamentous fungi and yeasts as the result of uncoupled respiration
18 (Karley *et al.*, 1997). Finally, it has been established that endocrine disrupters can interfere
19 with flavonoid signalling during plant-bacterial symbiosis (Fox *et al.*, 2001). To our
20 knowledge, experiments have seldom been performed taking into account NP already present
21 in the sludge, then the amendment of soil with the contaminated sludge. Using this
22 experimental approach, Gejlsbjerg *et al.* (2001) were unable to demonstrate a negative impact
23 of NP on bacterial denitrification, nitrification or aerobic respiration in soils.

24 The objective of the present study was to assess the impact of NP on soil fungal populations
25 as a result of contaminated sludge application. Adverse effects on the soil ecosystem depend
26 on the bioavailability, degradation and toxicity of the contaminant. The fate of NP in soil has
27 been previously published (Dubroca *et al.*, 2003). We examine here 1) the potential
28 concentration of NP to which soil organisms may be exposed, 2) the relevant toxicity by
29 studying endpoints related to fungal growth (biomass production) and reproduction
30 (sporulation and germination of spores).

31

1 **Materials and Methods**

2

3 **Chemicals**

4 4-*n*-Nonylphenol (4-*n*-NP) was obtained from Lancaster, whereas technical NP (NP) was
5 obtained from Fluka. Other chemicals were available from Sigma. Labelled 4-*n*-NP (2 GBq
6 mmol⁻¹, radiochemical purity > 99%) was a generous gift of Dr J.-P. Cravedi (INRA,
7 Toulouse).

8

9 **Soil and sludge characteristics**

10 The soil used in this study was a silt loam, comprising 25.5% sand, 55.0% silt and 19.5%
11 clay. Its organic matter content was 1.65%. The soil pH was 8.1 and the cationic exchange
12 capacity was 10.2 meq 100 g⁻¹. The soil, collected in the 10-20 cm layer in a field, was sieved
13 (2-mm) and used immediately.

14 Two types of sludge exhibiting different characteristics were applied on soils (Table 1). The
15 sludge from Ambares (SA) was formed following the treatment of both urban (90,000
16 equivalent inhabitants) and industrial wastewaters, whereas that from Plaisir (SP) collected
17 mostly urban wastewater (42,000 equivalent inhabitants).

18

19 **Bioavailability of NPs**

20 Amounts of NP bioavailable for soil fungi were determined using the protocol described by
21 Gaillardon (1995). Soil and soil/sludge samples (10 g equivalent dry matter) were placed in 5-
22 cm diameter Petri dishes to give a 3-4 mm thick layer. Aqueous solutions of unlabelled NP
23 and labelled (4.0 kBq) 4-*n*-NP were applied to the surface of the soil alone by pipette to
24 ensure 80 % of the moisture holding capacity of the soil, and a final concentration of 40 mg
25 kg⁻¹. Sludge samples were spiked with the mixture to allow the same final NP concentration
26 in the soil. After adding the chemical, the solvent (acetone) was left to evaporate for 30 min.
27 The chemicals were sorbed to the sludge for 24 hours at 4°C under nitrogen atmosphere
28 before the sludge was mixed with the soil. Soil/sludge ratio was 95/5 on a dry weight basis.
29 All the dishes were placed in the dark at 4°C to avoid biotransformation.

30 Concentrations of NP in the soil solution were determined 4 hours after treatment (soil alone)
31 or mixing (with sludge). Two superposed 42.5 mm diameter glass micro fibre filters GF/A
32 (Whatman) were laid on the soil surface and a slight pressure was applied for 10 s to favour
33 wetting of the filters. The upper filter was then recovered. The volume of soil solution and the

1 dissolved radioactivity retained in the filter were determined by weighing and liquid
2 scintillation counting.

4 **Adsorption isotherms**

5 Adsorption isotherms were obtained using the batch equilibrium method. Aliquots of 25 mL
6 of 0.05, 0.10, 0.15, 0.20, 0.30 and 0.40 mg L⁻¹ water solutions of NP (unlabelled NP and
7 labelled 4NP) supplemented with 10⁻² M CaCl₂ were added to 5 g of soil or soil/sludge
8 mixture, in centrifuge glass tubes. Equilibration was achieved by stirring for 24 hours at 20°C.
9 5-ML aliquots of the supernatants were removed by centrifugation at 4220 g for 30 min and
10 immediately analyzed. Concentrations of free NP in the supernatant (the equilibrium
11 concentrations, C_e) were determined by liquid scintillation counting. Control blanks were run
12 in parallel to measure tube-wall adsorption of NP. Adsorption data were fitted with the
13 Freundlich equation, $x/m = KCe^{1/n}$, where x/m is the amount of NP adsorbed in mg kg⁻¹, and
14 C_e is the equilibrium solution concentration of NP in mg L⁻¹. The constant K is a measure of
15 the magnitude of adsorption, or adsorption capacity of the sorbent.

17 **Fungi**

18 The fungal strains *Fusarium oxysporum*, *Fusarium solani* and *Mucor racemosus* used in this
19 study were all isolated from soil samples. The white-rot fungi *Phanerochaete chrysosporium*
20 and *Trametes versicolor* were obtained from the ATCC (referenced as 24725 and 32745,
21 respectively). They were maintained at 4°C on agar plates.

23 **Fungal liquid cultures and preparation of suspensions of spores**

24 Fungal strains used to produce suspensions of spores were grown on a culture medium
25 already published, containing glycerol (*P. chrysosporium*, Mougín *et al.*, 1994) or maltose (all
26 other strains, Lesage-Meesen *et al.*, 1996) and ammonium tartrate as carbon and nitrogen
27 sources. A mycelial mat on agar plugs (10 mm diam) was inoculated into 10 ml of the culture
28 medium in a 150-mL Erlenmeyer flask. Cultivation was carried out statically in the dark at
29 25°C. After 8-12 days of growth, the spores were harvested by shaking the cultures with glass
30 beads, counted and conditioned as liquid suspensions containing $2.5 \pm 0.5 \cdot 10^6$ spores mL⁻¹ for
31 inoculation.

1 **Short-term toxicity assessment**

2 Culture media were supplemented with NP ranging from 10^{-3} to 10^{-7} M immediately after
3 inoculation (acetic solutions, 50 μ L per Erlenmeyer). Effect of NP on spore germination
4 was determined after a 24-hour exposure by calculating the germinating rate. Fungal biomass
5 was separated from the medium after 2, 4 and 8 days of culture and dried overnight at 105°C
6 for dry weight determination. Effect of NP on sporulation was estimated by harvesting the
7 spores formed from the cultures and inoculating them in liquid media not supplemented with
8 NP. The germinating rate was also calculated after 24 hours.

9

10 **Long-term toxicity assessment**

11 Suspensions of spores were used to inoculate Erlenmeyers containing 10-mL liquid media
12 supplemented with 5.0×10^{-6} M NP, or solutions of the chemical diluted by 2 at each
13 inoculation to reach 3.1×10^{-7} M at the end of the experiment. The cultures were then allowed to
14 grow and sporulate in the dark at 25°C for 10 days. Spores were harvested as described above
15 and the experiments were still repeated 4-times. Fungal biomass was measured on a dry
16 weight basis. Germination and sporulation were expressed as a spore multiplication factor
17 (SMF), which reflects the ratio between the amounts of spores produced by a culture versus
18 the amounts of spores used for inoculation.

19

20 **Laccase induction**

21 Cultivation was carried out as described above for 4 days. After this time, ethanolic solutions
22 of NP or 4NP were added to the cultures to give 0.5×10^{-3} M (100 μ l solution per Erlenmeyer
23 flask). Aliquots were assayed for laccase activity after a further 3-day incubation.

24

25 **Laccase activity measurements**

26 Laccase production was assessed by measuring enzymatic oxidation of 2,2'-azinobis-(3-
27 ethylbenzothiazoline-6-sulfonic acid)(ABTS) at 420 nm ($\epsilon = 3.6 \times 10^4 \text{ cm}^{-1} \text{ M}^{-1}$) according to
28 Wolfenden & Wilson (1982). The reaction mixture contained 20 μ l extracellular fluid and 980
29 μ l 1 mM ABTS in 0.1 M KH_2PO_4 /citric acid buffer (pH 3.0) at 30°C . The buffer solution was
30 saturated with air by bubbling prior to the experiment. One unit of enzyme activity is defined
31 as the amount of enzyme that oxidises one μ mol ABTS in one min.

32

1 **Experimental design**

2 Each experiment was carried out in triplicate. Results are expressed as means \pm SD. IC₅₀ were
3 calculated by non linear regression analysis. In several experiments, a Student's *t*-test was
4 performed to determine significant differences.

6 **Results**

8 **Exposure assessment of soil fungi to NPs**

9 The two sludges contained high levels of NP (Table 1). SA was spiked with additional NP to
10 ensure a final concentration of 40 mg kg⁻¹ chemical after sludge application. That
11 experimental design allowed us to calculate the half-lives of NPs in soil, before and after
12 sludge application (Dubroca et al., 2003). The value was 4 days in the non-amended soil, and
13 it increased to 16 and more than 16 days after application of SA and SP, respectively. In the
14 latter case, a lag phase of 8 days in NPs biotransformation suggested the complete
15 inactivation of the endogenous microflora by the sludge.

16 These results incited us to measure NPs concentration in soil solutions for non-amended and
17 amended soils. Values obtained were 1.93 \pm 0.23 mg L⁻¹ for the soil alone, 1.46 \pm 0.73 mg L⁻¹
18 for the soil/SA mixture, 0.083 \pm 0.004 mg L⁻¹ for the soil/SP mixture. Mean values
19 corresponded to concentrations of 8.8 10⁻⁶ M NP for the non-amended-soil solution, 6.6 10⁻⁶
20 M (after SA application: A-limit) and 3.8 10⁻⁷ M (after SP application: P-limit) NPs in soil
21 solutions (Table 2).

23 Experimental data for adsorption of NP to the soil and the soil/sludge mixtures resulted in a
24 good fit according to the Freundlich equation (correlation coefficient significant at the 0.05
25 level). Adsorption data for the non-amended soil fitted with a non linear isotherm (L-type, 1/n
26 <1), while data for the two amended soils were better described by a linear isotherm (C-type,
27 1/n \approx 1)(Table 2). K values for the soil alone and the soil amended with SA were similar,
28 suggesting no great change of adsorption of NP due to sludge A application. By contrast, SP
29 application led to an increased adsorption of NP, with a 20-fold enhanced K constant.

31 **Short-term toxicity of NP on fungi**

32 We examined the dose-response relationship between NP concentration (ranging from 10⁻³ to
33 10⁻⁷ M) and the development of fungi in liquid cultures. Only 4 fungal strains, namely *P.*
34 *chrysosporium*, *F. oxysporum*, *F. solani* and *M. racemosus* produced spores in our culture

1 conditions, whereas *T. versicolor* was unable to sporulate. This strain was inoculated as
2 mycelial mats grown on agar plugs.

3 We first calculated the concentrations decreasing the germination of spores by 50% after 24
4 hours (IC₅₀) compared to untreated controls (Table 3). Our results showed that the “mother”
5 spores obtained from *P. chrysosporium* were very sensitive to NP, with a IC₅₀ of 7.5 10⁻⁶ M
6 on germination rate. This value is similar to A-limit. The “mother” spores obtained from the 3
7 other strains were affected to a lesser extent.

8 We then studied the impact of NP on fungal growth by measuring biomass dry weight after 2,
9 4 and 8 days of culture in the presence of NP. Fungal sensitivities to NP varied according to
10 the chemical concentration and the duration of the growing period (Table 3). The white-rot
11 fungi *T. versicolor* and *P. chrysosporium* grew in all treatment conditions and were the least
12 sensitive to NP, with concentrations causing 50% inhibition (IC₅₀) globally amounting to 10⁻⁴
13 and 5.0 10⁻⁴ M after 2 and 4 days for the second strain. Only a slight inhibiting effect of NP
14 was observed concerning the growth of *T. versicolor* at 10⁻³ M, the higher concentration
15 tested. The growth of *F. solani* was also less sensitive to NP than that of *M. racemosus* and *F.*
16 *oxysporum*. For these last two strains, CI₅₀ were globally comprised between 5.0 10⁻⁶ and 5.0
17 10⁻⁵ M, respectively. In all cases, the adverse effect of NP on fungal growth observed on day
18 2, was decreased at day 4, and totally disappeared after 8 days of incubation. We were unable
19 to observe a lethal effect (LC₁₀₀) of NP on *T. versicolor* (fungal growth from agar plugs), *P.*
20 *chrysosporium* and *F. solani* (germination of “mother” spores) in our experimental
21 conditions, whereas the growth of *M. racemosum* and *P. oxysporum* was totally inhibited with
22 10⁻⁴ M NP. Only IC₅₀ calculated for *M. racemosum* and *P. oxysporum* were comprised
23 between the A- and P-values measured for NP concentration in the soil solution.

24 In addition, high doses of NP (above 10⁻⁴ M) induced morphological defects in *F. solani*
25 hyphae. In summary, NP treatment resulted in a swelling of hyphae, associated with the loss
26 of hyphal apical dominance, and increased branching (data not shown).

27 Finally, we studied the ability of “daughter” spores produced by fungi grown in the presence
28 of NP to germinate in media free of the chemical. Their sensitivity appeared somewhat
29 increased regarding those of “mother” spores, as calculated IC₅₀ values were 2- to 80-fold
30 lower (Table 3).

31 In addition, the suspensions of “daughter” spores obtained from the two strains of *Fusarium*
32 grown in the presence of high concentrations of NP included numerous small spores
33 (microspores) which were not able to germinate within the 24-hour period taken into account
34 (data not shown).

1 IC₅₀ values influencing fungal growth and reproduction are in most cases higher than A-limit,
2 the highest value measured for the amount of NP bioavailable in soil solutions.

4 **Long-term toxicity of NP on fungi**

5 We examined the effect of NP on fungi following 5 cycles of biological events that could
6 affect the size of fungal populations, namely spore germination, biomass formation and spore
7 production. Three culture conditions were used: controls without NP, assays under constant
8 NP concentration of 5.0 10⁻⁶ M (below most of the IC₅₀ values calculated above), and assays
9 under decreasing concentrations of NP, thus reaching 3.1 10⁻⁷ M at the end of the experiment.
10 These decreasing values mimic the natural disappearance of the chemical in the soil due to its
11 transformation. These concentrations are consistent with P- and A-limits.

12 The calculated SMF, integrating both the production and germination of spores, varied
13 according to the strains. As a general case, the SMF naturally decreased in control cultures
14 after successive exposure of spores to NP, with a maximal effect between the two first
15 generations (Figure 1). NP also affected diversely this endpoint. A slight negative impact of
16 NP on *P. chrysosporium* SMF was significant only at the beginning of the experiments, whilst
17 a stronger effect was noticed throughout the experiment regarding *M. racemosus* and *F.*
18 *solani*. For these three strains, the effect did not seem related to NP level in the medium. The
19 most intensive impact of NP on fungal SMF was observed on *F. oxysporum* cultures. The
20 SMF corresponding to this strain dramatically decreased in the absence of the chemical. By
21 contrast, it increased up to 100 times by NP, with an effect increasing with the number of
22 biological cycles. In that case too, the pollutant level did not modulate the intensity of the
23 effect.

24 Biomass production in the control cultures tended to decrease as the number of biological
25 cycles increased (Figure 2). The presence of NP had a diverse effect on this decrease
26 depending on the fungal strains considered. No significant impact (at the 0.05 level) could be
27 observed when *P. chrysosporium* and *M. racemosus* were exposed to constant or decreasing
28 levels of NP. By contrast, a significant effect of NP was observed for *F. solani* and *F.*
29 *oxysporum*, whose growth seemed to be stimulated in the presence of NP at least at the end of
30 the experiment, whatever the conditions of treatment.

32 **Induction of laccases by NP and 4NP**

33 Laccases are exocellular multicopper oxidases produced by numerous white-rot fungi. They
34 can be induced by xenobiotics (Mougin et al., 2002). The dose-response relationship between

1 NP concentration and laccase induction was investigated in liquid cultures of *T. versicolor* by
2 measuring ABTS oxidation. Laccase activity in the control amounted to $0.16 \pm 0.02 \text{ U mL}^{-1}$
3 after 3 days of treatment (Figure 3). It was enhanced by 3 to 4 for NP concentrations ranging
4 from 10^{-7} to 10^{-5} M in the medium. These values were consistent with the A- and P-limits. At
5 higher concentrations, laccase activity increased with NP doses. Among the isomers, 4NP was
6 shown to be a potent inducer thus increasing laccase activity by 14 after 3 days at 5×10^{-4} M.
7 Between 10^{-6} and 10^{-4} M, NP was also shown to increase lignin peroxidase production 3 fold
8 in *P. chrysosporium* cultures (data not shown).

9

10 **Discussion**

11

12 Application of wastewater sludge on agricultural soils raises questions about the
13 bioavailability of organic pollutants for living organisms and their possible negative impact
14 on the exposed organisms.

15 The amounts of chemicals bioavailable for soil micro-organisms are rarely determined. Our
16 results concerning the amount of NP measured in the soil solution under several adsorbents
17 (soil or soil/sludge mixtures) depend on the physico-chemical properties of the sludges. They
18 demonstrate the decrease in bioavailability of NP following the application of the sludge from
19 Plaisir onto the soil. Nevertheless, these amounts remain easily measurable, and our
20 experiments provide minimum and maximum values for the concentrations of NP that can be
21 used in fungal liquid cultures to assess the impact of the chemical in realistic environmental
22 situations.

23 Experimental data for adsorption of NP to the soil and the soil/sludge mixtures resulted in a
24 good fit to the Freundlich equation. Nonlinear L-shaped isotherms indicated that our non-
25 amended soil has a moderate affinity for NP in the initial stages of adsorption (Giles et al.,
26 1960, 1974). Linear C-type isotherms obtained in the presence of the two sludges suggested a
27 constant partition of NP between the solution and the adsorbent. The calculated adsorption
28 coefficient (K) for NP onto the soil/SP mixture was 20-fold higher than the value obtained
29 with the other adsorbents, evidencing a higher extent of adsorption of NP in SP. These results
30 agree with the lower amount of NP (two orders of magnitude) measured in the soil solution
31 using static measurement. In soils, it has been reported that phenolic compounds of moderate
32 hydrophobicity adsorb onto organic matter. Application of the sludges with similar amounts
33 of organic matter resulted in distinct effects on adsorption, thus suggesting the involvement of
34 other parameters, such as their chemical composition. Taken together, our data provide

1 information for the first time on exposure of soil micro-organisms to NP. They show that the
2 bioavailability of NP can be significant when applied to soil following incorporation into
3 sludge. In the absence of measured data, calculated predicted environmental concentrations
4 (PEC) amounted to 2-4 mg kg⁻¹ (APE Research Council, 2002). The soil contamination used
5 in our study was 10-fold higher, in order to take into account the worst case hypothesis, such
6 as massive soil amendment with heavily contaminated sludge.

7
8 Impact of NP on fungi was then assessed using 3 strains isolated from soils (namely *F. solani*,
9 ascomycete; *M. racemosus*, zygomycete, *F. oxysporum*, deuteromycete) and two white-rot
10 basidiomycetes from our collection (*P. chrysosporium* and *T. versicolor*) that could also be
11 found in soils. Endpoints taken into account concern reproduction (production and
12 germination of spores) and growth (biomass production), both governing the size of the
13 fungal populations. It is difficult to assess an impact on fungal populations directly grown in
14 soils. For this reason, some experiments were performed using fungal liquid cultures.

15 Short-term (acute) toxicity of NP was assessed first. Generally, the germination rate of fungal
16 spores seemed moderately sensitive to exposure to NP in environmentally-sound amounts.
17 Nevertheless, even in the presence of higher amounts of NP, inducing a strong inhibition of
18 germination, the consequences on the size of the resulting populations were slight. In fact, an
19 adverse effect of NP on fungal growth was only detected in young fungal cultures, in the 2
20 days following the treatment with the chemical. This kind of lag phase in growth has already
21 been reported concerning *Neurospora* cultures exposed to NP with similar IC₅₀ values (Karley
22 et al., 1997). This effect was reduced after 4 days of culture, and totally suppressed after 8
23 days. These results suggest that nutrient availability remains the main factor governing fungal
24 growth, as soon as the spores germinate. In our experiments, most of the calculated IC₅₀ for
25 fungal growth (after 2 days of exposure) and spore germination were in the 1-10 10⁻⁶ M
26 range. They compare well with the acute concentrations causing 50% lethality or inhibition in
27 fish, amphibian, invertebrate, mollusc or algae species (Weinburger et al., 1987; Servos,
28 1999). They were below the values reported to inhibit bacterial nitrification (Gejlsbjerg et al.,
29 2001).

30 However, exposure to NP at doses higher than these resulting from soil amendment under
31 good agricultural practice is not without other effects on fungi. An uncoupling effect of NP on
32 respiration has already been described in liquid cultures supplemented with high
33 concentrations of the chemical (Karley et al., 1997). These authors also reported
34 morphological defects in hyphae in *Neurospora crassa*, consisting in a swelling of hyphae

1 associated with the loss of hyphal apical dominance and increased branching. These
2 abnormalities could be due to disruption of the hyphal free cytosolic Ca^{2+} gradient, the H^+
3 gradient, and the actin cytoskeleton of the apical cells (Jackson and Heath, 1993; Karley et al.,
4 1997). We observed these abnormalities in *Fusarium solani* cultures (another ascomycete), as
5 well as the formation of immature microspores. These results must be considered from an
6 ecological point of view, because ascomycetes represent the main populations of soil fungi. In
7 contrast, our results show that the white-rot basidiomycetes studied appeared less sensitive to
8 NP than the other strains.

9 Possible long-term (chronic effects) were also investigated. We decided to integrate both the
10 production and germination of the spores in a global index named the spore multiplication
11 factor (SMF). The decrease often observed in the non treated cultures reflects the loss of
12 performance of the fungal strains due to natural nutrients possibly missing in our synthetic
13 culture media. Nevertheless, both an increase of the SMF or its decrease suggest a chemical
14 stress caused by NP. In chronic toxicity tests, no observable effect concentration (NOEC) has
15 been determined as low as 10^{-5} M in fish and 10^{-8} M in invertebrates (Servos, 1999).
16 Threshold for chronic toxicity on organisms living in sediments was 10^{-5} M (APE Research
17 Council, 2002). Our data showed that a constant exposure of some fungal strains to $5.0 \cdot 10^{-6}$ M
18 NP modified their sporulation.

19 How NP can modify the reproduction of fungi remains to be elucidated. It has long been
20 established that inhibition of the germination rate is mainly due to an effect on respiration, a
21 typical mode of action of fungicide compounds (Leroux, 1996). However, little is known on
22 the endogenous factors affecting sporulation, such as sexual hormone signalling. On one
23 hand, several fungi are able to produce or metabolize several steroid hormones, thus affecting
24 fungal growth and development (Brasch, 1997; Rizner et al., 1999; Rizner and ZakeljMavric,
25 2000). On the other hand, trisporic acid is a sexual hormone of zygomycetes, which triggers
26 the first steps of zygophore formation (Czempinski et al., 1996). It is likely that NP, a well-
27 known endocrine disrupter, may interfere with these sexual hormone pathways. The growth of
28 *P. chrysosporium* and *M. racemosus* was not affected by NP in our experimental conditions
29 maintained during 5 biological cycles.

30

31 NP has also been shown to induce laccase production. 4NP is a more potent inducer than the
32 complete mixture. This effect on extracellular oxidases may be considered as a positive effect,
33 because it leads to a decreased bioavailability of the chemical and to its increased
34 detoxication. This reaction may also lead to the stabilization of the chemical in the soil, thus

1 preventing groundwater contamination. As demonstrated earlier (Mougin et al., 2002), our
2 present results confirm that xenobiotics can be potent inducers of extracellular enzymes of the
3 ligninolytic pathway on fungi, even in low concentrations.

4
5 The relative tolerance to NP exhibited by several fungal strains could be related to their high
6 efficiency in transforming NP. For example, white-rot basidiomycetes (*P. chrysosporium* and
7 *T. versicolor*) are known to secrete extracellular oxidases (peroxidases and/or laccases) that
8 are able to catalyze the rapid polymerization of NP through oxidative coupling (Tsutsumi et
9 al., 2001; Dubroca et al., 2003). The reaction located in the culture medium efficiently
10 reduced the bioavailability and toxic impact of the chemical. In addition, zygomycetes
11 including *Cunninghamella* and *Mucor* sp. are known to possess intracellular P450 systems
12 able to efficiently transform pollutants (Mougin, 2002).

13 14 **Conclusions**

15
16 These preliminary experiments show that the potential of NP from sewage sludge applications
17 to have an adverse impact on soil fungi is rather low, because of reduced exposure to the
18 chemical. Nevertheless, it remains necessary to develop extensive chemical monitoring and
19 toxicity studies in order to evaluate much more accurately the possible impact of organic
20 compounds present in sludge used as soil amendment. These points should be completed by
21 physiological and biochemical studies to better identify the modes of action of NP on fungi.

22 23 **Acknowledgements**

24 The authors thank Christine Young (INRA, Jouy-en-Josas) for proofreading the manuscript.

1 **REFERENCES**

2

3 Ahel, M. and W. Giger. 1985. Determination of alkylphenols and alkylphenol mono- and
4 diethoxylates in environmental samples by high-performance liquid chromatography. *Anal.*
5 *Chem.* 57:1577-1583.

6 Ahel, M., W. Giger, M. Koch. 1994a. Behaviour of alkylphenol polyethoxylate surfactants in
7 the aquatic environment – I. Occurrence and transformation in sewage treatment. *Water*
8 *Res.* 28:1131-1142.

9 Ahel, M., W. Giger, C. Schaffner. 1994b. Behaviour of alkylphenol polyethoxylate
10 surfactants in the aquatic environment – II. Occurrence and transformation in rivers. *Water*
11 *Res.* 28:1143-1152.

12 APE Research Council. 2002. A preliminary assessment of ecological risks from nonylphenol
13 in municipal sewage sludge following wastewater treatment.
14 http://www.aperc.org/docs/preliminary_eco_risks_from_sludge_042402.pdf.

15 Bokern, M., P. Raid, H. Harms. 1998. Toxicity, uptake and metabolism of 4-*n*-nonylphenol in
16 root cultures and intact plants under septic and aseptic conditions. *Environ. Sci. Pollut.*
17 *Res.* 5:21-27.

18 Brasch, J. 1997. Hormones, fungi and skin. *Mycoses* 40:11-16.

19 Czempinski, K., V. Kruft, J. Wostemeyer, A. Burmester. 1996. 4-Dihydromethyltrisporate
20 dehydrogenase from *Mucor mucedo*, an enzyme of the sexual hormone pathway:
21 purification, and cloning of the corresponding gene. *Microbiology* 142:2647-2654.

22 Dubroca, J., A. Brault, A. Kollmann, I. Touton, C. Jolival, L. Kerhoas, and C. Mouglin. 2003.
23 Biotransformation of nonylphenol surfactants in soils amended with contaminated sewage
24 sludges. *In* E. Lichtfouse, S. Dudd, D. Robert (eds) *Environmental Chemistry*. Springer-
25 Verlag, Heidelberg, Germany (in press).

1 Fox, J.E., M. Starcevic, K.Y. Kow, M.E. Burow, J.A. McLachlan. 2001. Endocrine disrupters
2 and flavonoid signalling. *Nature* 413:118-129.

3 Gaillardon, P., and J.C. Dur. 1995. Influence of soil moisture on short-term adsorption of
4 diuron and isoproturon by soil. *Pestic. Sci.* 45:297-303.

5 Gejlsbjerg, B., C. Klinge, L. Samsoe-Petersen, and T. Madsen. 2001. Toxicity of linear
6 alkylbenzene sulfonates and nonylphenol in sludge-amended soil. *Environ. Toxicol. Chem.*
7 20:2709-2716.

8 Giles, C.H., T.H. MacEvan, S.N. Nakhwa, and D. Smith. 1960. Studies in adsorption. Part XI.
9 A system of classification of solution adsorption isotherms, and its use in diagnosis of
10 adsorption mechanisms and in measurement of specific surface areas of solids. *J. Chem.*
11 *Soc.* III:3973-3993.

12 Giles, C.H., D. Smith, and A. Huitson. 1974. A general treatment and classification of the
13 solute adsorption isotherm. *J. Colloid Interface Sci.* 47:755-765.

14 Hesselsoe, M., D. Jensen, K. Skals, T. Olesen, P. Moldrup, P. Roslev, G.K. Mortensen, and
15 K. Henriksen. 2001. Degradation of 4-nonylphenol in homogeneous and nonhomogeneous
16 mixtures of soil and sewage sludge. *Environ. Sci. Technol.* 35:3695-3700.

17 Jackson, S.L., and L.B. Heath. 1993. Role of calcium ions in hyphal tip growth. *Microbiol.*
18 *Rev.* 57:367-382.

19 Jolival, C., A. Raynal, E. Caminade, B. Kokel, F. Le Goffic, and C. Mougin. 1999.
20 Transformation of N',N'-dimethyl-N-(hydroxyphenyl)ureas by laccase from the white rot
21 fungus *Trametes versicolor*. *Appl. Microbiol. Biotechnol.* 51:676-681.

22 Jontofsohn, M., M. Stoffels, A. Hartmann, G. Pfister, I. Jüttner, G. Severin-Edmair, K.-W.
23 Schramm, M. Schloter. 2002. Influence of nonylphenol on the microbial community of
24 lake sediments in microcosms. *Sci. Total Environ.* 285:3-10.

1 Karley, A.J., S.I. Powell, J.M. Davies. 1997. Effect of nonylphenol on growth of *Neurospora*
2 *crassa* and *Candida albicans*. Appl. Environ. Microbiol. 63:1312-1317.

3 Leroux, P. 1996. Recent developments in the mode of action of fungicides. Pestic. Sci.
4 47:191-197.

5 Lesage-Meesen, L., M. Delattre, M. Haon, J.F. Thibault, B. Colonna Ceccaldi, P. Brunerie,
6 M. Asther. 1996. A two-step bioconversion process for vanillin production from ferulic
7 acid combining *Aspergillus niger* and *Pycnoporus cinnabarinus*. J. Biotechnol. 50:107-
8 113.

9 Machala, M., J. Vondracek. 1998. Estrogenic activity of xenobiotics. Vet. Med. Czech
10 43:311-317.

11 Mougin C., 2002. Bioremedaition and phytoremediation of industrial PAH-polluted soils.
12 Polycycl. Aromat. Comp. 22:1011-1043.

13 Mougin C., A. Kollmann, and C. Jolivalt. 2002. Enhanced production of laccases by the
14 fungus *Trametes versicolor* by the addition of xenobiotics. Biotechnol. Letters 24:139-142.

15 Mougin, C., C. Laugero, M. Asther, J. Dubroca, P. Frasse, and M. Asther. 1994.
16 Biotransformation of the herbicide atrazine by the white rot fungus *Phanerochaete*
17 *chrysosporium*. Appl. Environ. Microbiol. 60:705-708.

18 Nilsson, R. 2000. Endocrine modulators in the food chain and environment. Toxicol. Pathol.
19 28:420-431.

20 Rizner, T.L., G. Moeller, H.H. Thole, M. ZakeljMavric, J. Adamski. 1999. A novel 17 beta-
21 hydroxysteroid dehydrogenase in the fungus *Cochliobolus lunatus*: new insights into the
22 evolution of steroid-hormone signalling. Biochem. J. 337:425-431.

23 Rizner, T.L., M. ZakeljMavric. 2000. Characterization of fungal 17 beta-hydroxysteroid
24 dehydrogenases. Comp. Biochem. Physiol. B. – Biochem. Mol. Biol. 127:53-63.

- 1 Servos, M.R. 1999. Review of the aquatic toxicity, estrogenic responses and bioaccumulation
2 of alkylphenols and alkylphenol polyethoxylates. *Water Qual. Res. J. Can.* 34:123-177.
- 3 Soto, A.M., H. Justicia, J.W. Wray, and C. Sonnenschein. 1991. P-Nonylphenol: an estrogen
4 xenobiotic released from modified polystyrene. *Environ. Health Perspect.* 92:167-173.
- 5 Sumpter, J.P. 1998. Xenoendocrine disrupters – environmental impacts. *Toxicol. Letters* 102-
6 103:337-342.
- 7 Topp, E., and A. Starratt. 2000. Rapide mineralization of the endocrine-disrupting chemical 4-
8 nonylphenol in soil. *Environ. Toxicol. Chem.* 19:313-318.
- 9 Tsutsumi, Y., T. Haneda, T. Nishida. Romoval of estrogenic activities of bisphenol A and
10 nonylphenol by aoxidative enzymes from lignin-degrading basidiomycetes. *Chemosphere.*
11 42:271-276.
- 12 Vos, J.V., E. Dybing, H.A. Greim, O. Ladefoged, C. Lambré, J.V. Tarazona, I. Brandt, and
13 A.D. Vethaak. 2000. Health effects of endocrine-disrupting chemicals on wildlife, with
14 special reference to the European situation. *Crit. Tev. Toxicol.* 30:71-133.
- 15 Weinburger, P., C. de Chacin, and M. Czuba. 1987. Effects of nonylphenol, a pesticide
16 surfactant, on some metabolic processes of *Chlamidomonas segnis*. *Can. J. Bot.* 65:696-
17 702.
- 18
- 19

1 Legends to figures

2

3 Figure 1. Impact of nonylphenol on the spore multiplication factor during long-term exposure
4 of fungal liquid cultures. Black bars refer to untreated controls, white bars to cultures treated
5 with constant concentration of the chemical, grey bars to cultures treated with decreasing
6 concentrations of the chemical.

7

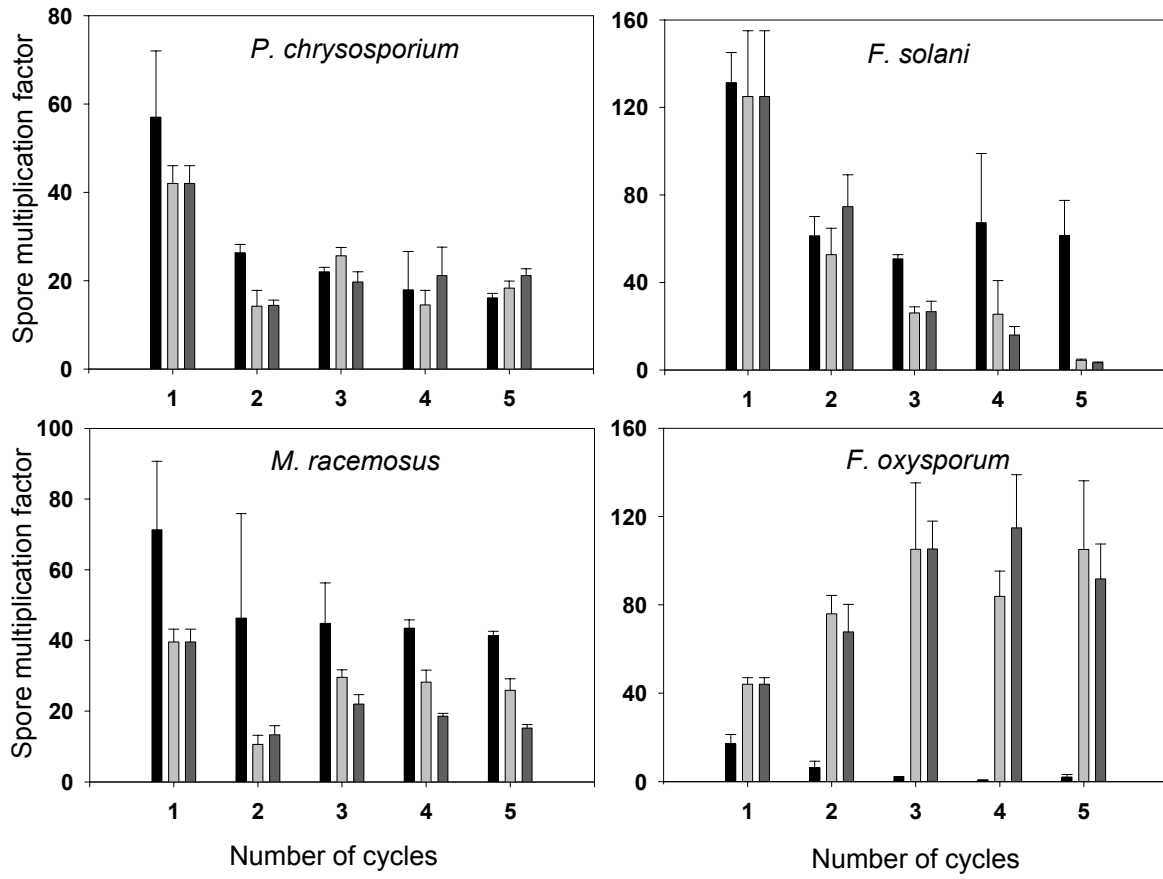
8 Figure 2. Impact of nonylphenol on biomass production during long-term exposure of fungal
9 liquid cultures. Black bars refer to untreated controls, white bars to cultures treated with
10 constant concentration of the chemical, grey bars to cultures treated with decreasing
11 concentrations of the chemical.

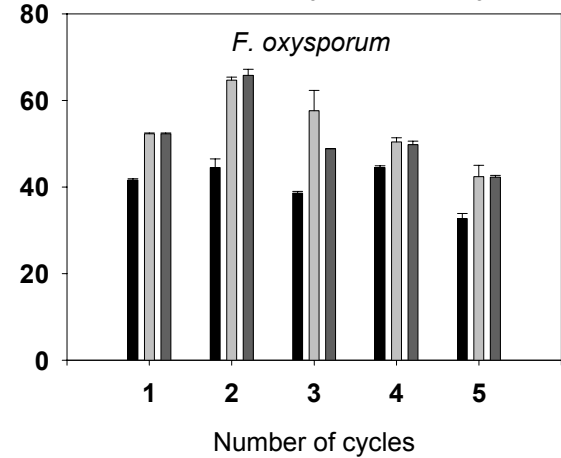
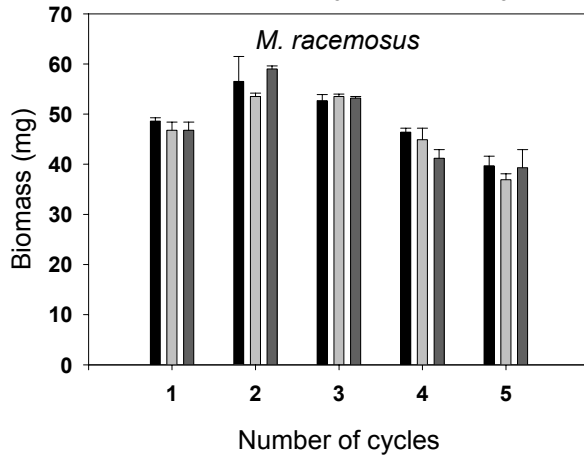
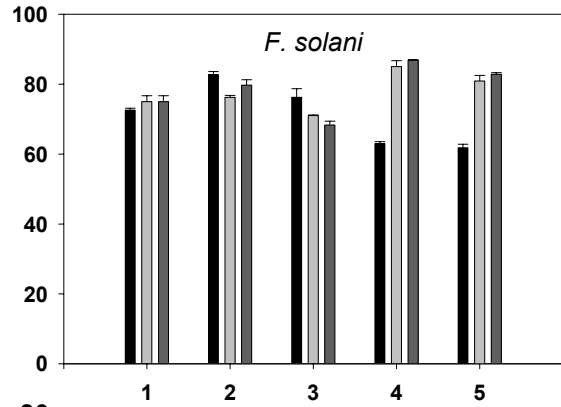
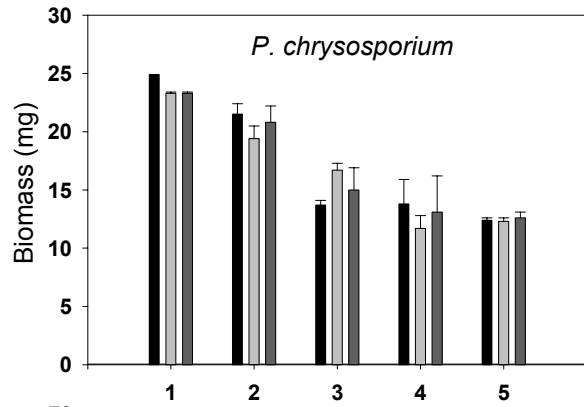
12

13 Figure 3. Impact of nonylphenol on laccase production in fungal liquid cultures of *Trametes*
14 *versicolor* after 3 days of exposure to the chemical.

15

16





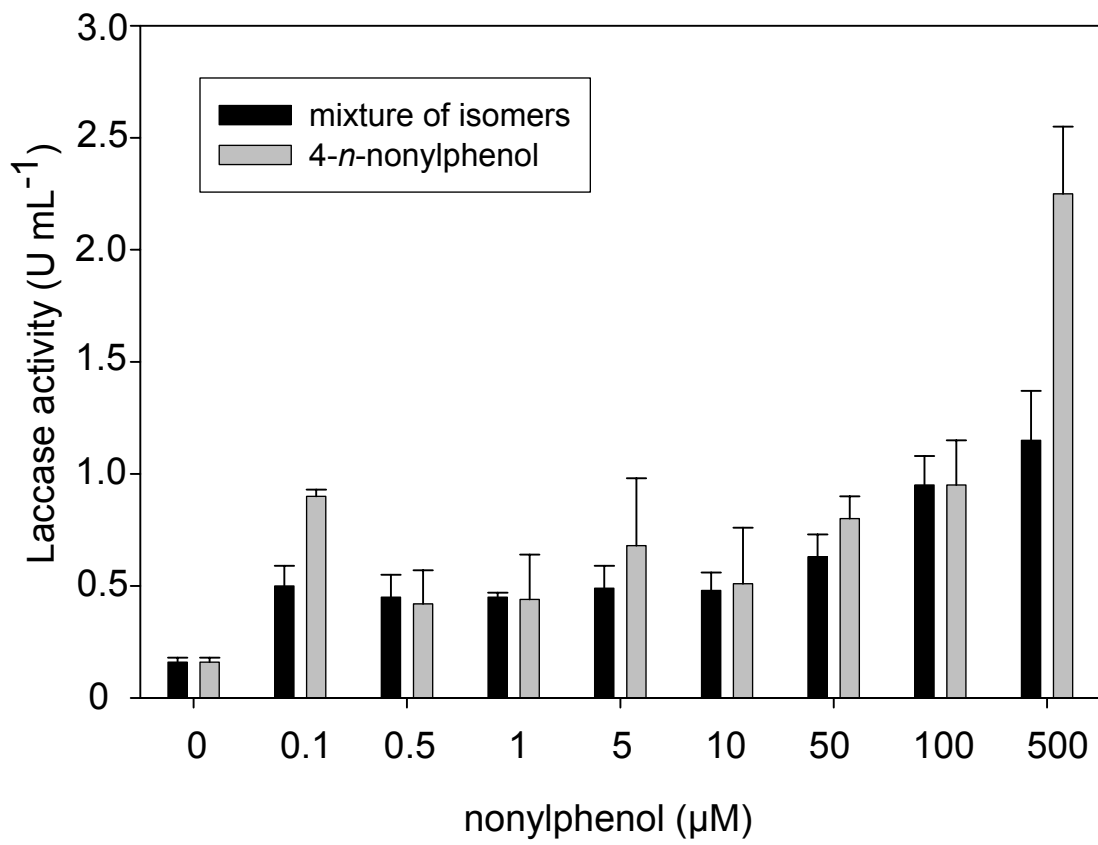


Table 1. Characteristics of the two types of sludge used in this study.

Parameter	Sludge from Ambares (SA)	Sludge from Plaisir (SP)
Origin	Ambares	Plaisir
Treatment of wastewater	aerobic digestion + anaerobic stabilization	aerobic digestion + anaerobic stabilization + adding of lime
Dry matter (%)	75.71	33.12
Organic matter of dry matter (%)	51.41	45.20
Total nitrogen of dry matter (%)	3.97	2.66
pH water	7.8	12.5
NPs content (mg kg ⁻¹ dry matter)	200.00	506.00
PAHs [†] content (mg kg ⁻¹ dry matter)	0.51	0.43
PCBs ^{††} content (mg kg ⁻¹ dry matter)	0.089	0.071
Metal ions [§] (mg kg ⁻¹ dry matter)	8880.71	113.86

[†]PAHs: fluoranthene, benzo[b]fluoranthene, benzo[a]pyrene.

^{††}PCBs: 28,52, 101, 118, 138, 153, 180.

[§]Metal ions: Fe, Mn.

Table 2. Exposure of soil fungi to NP in soils and soil/sludge mixtures.

Adsorbent	NP concentration in the soil solution (M)	Nonlinear correlation coefficient (r^2)	K (L kg ⁻¹)	1/n
Nonamended soil	$8.8 \cdot 10^{-6}$	0.995	45.3	0.79
Soil + sludge A	$6.6 \cdot 10^{-6}$	0.994	58.6	1.04
Soil + sludge P	$3.8 \cdot 10^{-7}$	0.998	1083.6	1.03

Table 3. Acute toxicity of NP on fungal strains in liquid cultures

Fungal strains	IC ₅₀ (M)			LC ₁₀₀ (M)	
	Germination of mother spores	Fungal growth after 2 days	Fungal growth after 4 days	Germination of daughter spores	Fungal development
<i>T. versicolor</i>	/	> 10 ⁻³	> 10 ⁻³	/	> 10 ⁻³
<i>P. chrysosporium</i>	7.5 10 ⁻⁶	10 ⁻⁴	5.0 10 ⁻⁴	2.5 10 ⁻⁶	> 10 ⁻³
<i>F. solani</i>	4.1 10 ⁻⁴	4.8 10 ⁻⁵	> 10 ⁻⁴	5.1 10 ⁻⁶	> 10 ⁻³
<i>M. racemosus</i>	10 ⁻⁴	5.1 10 ⁻⁶	5.3 10 ⁻⁵	5.9 10 ⁻⁵	10 ⁻⁴
<i>F. oxysporum</i>	2.9 10 ⁻⁵	5.0 10 ⁻⁶	5.1 10 ⁻⁵	5.1 10 ⁻⁶	10 ⁻⁴

Table 4. Impact of NP on fungal reproduction in liquid cultures

Fungal strains	CI ₅₀ F1 (M)	CI ₅₀ F2 (M)	microspores (M)
<i>P. chrysosporium</i>	7.5 10 ⁻⁶	2.5 10 ⁻⁶	n.o.
<i>F. solani</i>	4.1 10 ⁻⁴	5.1 10 ⁻⁶	10 ⁻⁴
<i>M. racemosus</i>	10 ⁻⁴	5.9 10 ⁻⁵	n.o.
<i>F. oxysporum</i>	2.9 10 ⁻⁵	5.1 10 ⁻⁶	6.9 10 ⁻⁵

n.o.: not observed