

AperTO - Archivio Istituzionale Open Access dell'Università di Torino

Is digestate safe? A study on its ecotoxicity and environmental risk on a pig manure

This is the author's manuscript

Original Citation:

Availability:

This version is available <http://hdl.handle.net/2318/1557828> since 2017-11-22T13:35:39Z

Published version:

DOI:10.1016/j.scitotenv.2016.02.004

Terms of use:

Open Access

Anyone can freely access the full text of works made available as "Open Access". Works made available under a Creative Commons license can be used according to the terms and conditions of said license. Use of all other works requires consent of the right holder (author or publisher) if not exempted from copyright protection by the applicable law.

(Article begins on next page)



UNIVERSITÀ DEGLI STUDI DI TORINO

This is an author version of the contribution published on:

Questa è la versione dell'autore dell'opera:

Sci Total Environ. 551-552 :127-132 2016

DOI: 10.1016/j.scitotenv.2016.02.004

The definitive version is available at:

La versione definitiva è disponibile alla URL:

<http://www.sciencedirect.com/science/article/pii/S0048969716302157>

TITLE: IS DIGESTATE SAFE? A STUDY ON ITS ECOTOXICITY AND ENVIRONMENTAL RISK ON A PIG MANURE

AUTHORS: Valeria Tigini^{1*}, Marta Franchino², Francesca Bona², Giovanna Cristina Varese¹

AFFILIATION: ¹ Mycotheca Universitatis Taurinensis, Department of Life Sciences and System Biology, University of Turin, viale Mattioli, 25, 10125 Turin, Italy.

² Laboratory of Aquatic Ecosystems, Department of Life Sciences and System Biology, University of Turin, via Accademia Albertina, 13, 10123 Turin, Italy.

***CORRESPONDING AUTHOR:** Mailing address: Department of Life Sciences and System Biology, University of Turin, viale Mattioli, 25, 10125 Turin, Italy. Phone: +39-011-6705964. Fax: +39-011-6705962. E-mail: valeria.tigini@unito.it

Abstract. Digestate represents a precious by-product in particular in agriculture, however its impact on the environment and human health is still unexplored. In this work, the toxicity of a pig slurry digestate was assessed through 7 ecotoxicity tests and considering 10 different endpoints. Besides, a synthetic index was applied to the outputs of the battery of tests for the environmental risk assessment, in order to evaluate the opportunity to use directly this kind of digestate in agriculture or to introduce an additional treatment. All the organisms were sensitive to digestate toxicity (EC₅₀ ranged from 14.22% for *Cucumis sativum* to 0.77% for *Raphidocelis subcapitata*). The physical-chemical features at the base of this toxicity seem to be the high content of ammonium, salinity, COD, phosphate and colour. The synthetic index showed that the digestate was very toxic and associated to an extremely high environmental risk. Thus a pre-treatment is needed to reduce its toxicity and environmental impact, whatever could

be its exploitation.

Key Words: Anaerobic digestion, bioassays, bacteria, algae, phytotoxicity, crustaceans.

1. Introduction

Intensive livestock breeding produces a large quantity of biodegradable wastes that have to be managed adequately. EU Landfill Directive (1999/31/EC) has underlined the importance of waste reduction and management with sustainable methods such as recycling and composting. Since the anaerobic digestion of agriculture and zootechnical wastes is of great value both for livestock waste management and biogas production, the number of composting and anaerobic digestion plants increased in all the Europe Countries (Holm-Nielsen et al., 2009). Italy is the third country in the world for biogas production, after Germany and China, with approximately 1300 plants and 7400 Gwh produced in 2013 (Baronchelli, 2015). Benefits of anaerobic digestion basically consist in the production of biogas, and the reduction of both greenhouse gas emissions and water pollution (Möller and Stinner, 2010). On the other hand, anaerobic digestion produces the digestate, a residual material that is rich in recalcitrant organic molecules and nutrients, thus it has to be adequately managed and disposed (Provenzano et al., 2011).

In the light of Directive 2008/98/EC, which gives an adding value to wastes by means of their integrated management, digestate addition to soil is considered an appropriate option, with multiple benefits for agriculture and environment by reducing the use of mineral fertilisers (Zhang et al., 2015). However, applications of biogas digestates and their impacts on the environment and human health are still unexplored

and the effectiveness of digestate as organic amendment and fertilizer is still under debate (Nkoa, 2014).

Ecotoxicity analyses of digestates before their exploitation in agriculture can predict their environmental impact and the necessity for additional treatments. Nevertheless, the few studies that have been done on this kind of samples used a limited number of bioassays and did not calculate a risk for the environment (Chen et al., 2014; Różyło et al., 2015). In ecotoxicity studies, indeed, the application of a battery of bioassays with organisms representing different positions in the food chain is essential, in order to obtain results that may realistically represent the impact on the environment. Moreover, the outputs of a battery should be summarised in a single datum, with the aim to give information about the environmental risk associated to the tested samples. This elaboration could allow to take decision for the digestate manage and use (Costan et al., 1992; Persoone et al., 2003; Canna-Michaelidou and Christodoulidou, 2008).

In the present study, the toxicity of a pig slurry digestate was assessed through 7 ecotoxicity tests and considering 10 different endpoints. Besides, the synthetic index developed by UNICHIM Water Quality Commission (UNICHIM, 2008) was used to for the environmental risk assessment, in order to evaluate the opportunity to use directly this kind of digestates in agriculture or to introduce an additional treatment.

2. Materials and Methods

2.1 Origin of samples and chemical analyses

Digestate was obtained from the effluent of an anaerobic digester, which treats pig slurry and corn, located in North West Italy. Samples of digestate liquid phase were stored at 4 °C after collection and analyzed periodically to check its stability for two

months during which all the experiments were carried out. Parameters measured for the chemical characterization of the digestate were: ammonium, nitrate, total nitrogen, phosphate and COD. They were selected on account of their usual abundance and potential impact on the environment. All of them were spectrophotometrically estimated (LASA 100-HACH LANGE) according to APAT-IRSA CNR Standard Methods 2003 for nutrients and ISPRA Metodo 5135” – 2014 for COD. Moreover, pH and conductivity were measured by using the probe WTW Multi340i.

2.2 Ecotoxicity tests

Seven ecotoxicity test were selected on account of data in literature about their sensitivity to toxic substances and their low cost and easy availability also for a private company. Moreover, some of them were selected on account of their recommendation in the European legislations (i.e. Italian law Dlgs 152/2006).

Vibrio fischeri strain NRRL B-11177 was bought at Ramcon A/S (Birkerød, Denmark) and used for the test of luminescence inhibition (UNI EN ISO 11348-3) with Microtox® toxicity system (Microtox Model 500; Microbics Corp., USA) as described by Tigini et al. (2011). The luminescence intensity in all cuvettes was measured before the addition of the wastewaters and after 15 and 30 min exposition and automatic colour correction was performed. A computer program for Microtox Acute Toxicity Test (Azur Environmental Ltd., UK) was used for the data elaboration.

Raphidocelis subcapitata (Korshikov) Nygaard et al., originating from Agenzia Regionale per la Protezione dell’Ambiente (ARPA Piemonte, Grugliasco, TO), was used for the algal growth inhibition (UNI EN ISO 8692:2005). The tests were

performed as described by Tigini et al. (2011), and data were elaborated using ToxCalc™ 5.0.

The aquatic plant *Lemna minor* L. was used for the assessment inhibition of both biomass dry weight and frond number (ISO SO/WD 20079). The test was performed as described by Casieri et al. (2008).

Cucumis sativus L. and *Lepidium sativum* L. were used for phytotoxicity tests (UNICHIM N. 1651, 2003). Seeds were purchased from Blumen Group S.p.A. (Piacenza) and the test was performed as described by Tigini et al. (2011).

Daphnia magna Straus, cultured at ARPA Piemonte, was used for the immobilisation test (UNI EN ISO 6341:99). The tests were performed as described by Tigini et al. (2011), and immobile animals were counted after both 24 h and 48 h.

In the *Artemia franciscana* L. bioassay, after a preliminary test, 3 dilutions were chosen with 3 replicates each and 3 repetitions were used for the control. Three dilutions of 100 mg *A. franciscana* cysts were placed in a Petri dish (5 cm diameter) for hatching, containing 12 mL of saltwater and incubating for 48 h at 25 °C in the dark (changing saltwater after 24 h). After the incubation, 10 instar I and II nauplii were inoculated in 1 mL of sample, or saltwater for the control, for each replicate. Nauplii were incubated for 24 h at 25 °C in the dark, after that the nauplii mortality was assessed.

The sensitivity of the test organisms cultivated in directly in laboratory (*D. magna*, *L. minor*, *R. subcapitata*) was periodically assessed with a potassium dichromate solution (K₂Cr₂O₇).

Results of ecotoxicity tests were plotted on a dose-effect chart; the EC₅₀ and its confidence limits (p = 0.05) and toxic units (100/EC₅₀) were estimated using standard procedures.

2.9 Synthetic index and ecotoxicological risk assessment

The synthetic index was developed by the Associazione per l'unificazione nel settore dell'industria chimica (UNICHIM) Commissione Qualità dell'Acqua, Gruppo di Lavoro Metodi Biologici, Sottogruppo Acque salate/salmastre e Sedimenti, Gruppo ad hoc Batterie, scale di tossicità e indici integrati. It is a modification of the model proposed by Hartwell (1997), and described by Baudo et al. (2011). This synthetic index allows to compare the results of ecotoxicity tests batteries through a toxicity score (BTS), that represents the mean of the relative toxicity of each test (RT_{endpoint}). This last parameter is calculated as follows:

$$RT_{\text{endpoint}} = 100 - 100 \cdot \frac{[\log (C \cdot EC_x) \cdot R \cdot S]_{\text{max}} - [\log (C \cdot EC_x) R \cdot S]_{\text{endpoint}}}{[\log (C \cdot EC_x) R \cdot S]_{\text{max}}} \quad [1]$$

where C is a statistical corrective (C = 2 if the EC_x is higher than 100%; C = 1 if the EC_x and its 95% confidence limits are lower than 100%); S is a score depending on the considered endpoint (mortality = 8; bioluminescence = 7; development = 6; reproduction = 5; growth = 4; genotoxicity = 3; mutagenicity = 2, behaviour = 1); R is the rank of toxic concentrations and it is assigned from the lowest concentration to the highest one.

The synthetic index evaluates also the risk score of the battery (BRS) on the base of the consistence hat indicates the agreement rate among different endpoints, and is

calculated with this formula:

$$\text{consistence} = [(N/2)-X]^3 \quad [2]$$

where N is the number of the endpoints and X is the number of not significant (i.e. the EC_x is not calculable).

Thus, the higher the consistence the higher the risk score. Moreover, the total relevance is calculated as a percentage on the base of the severity of the kind of the considered endpoint, which affects the results with different weight.

Both the toxicity score and the risk score of the battery are converted in a scale based on the expert judgment (Baudo et al., 2011).

Eventually, the EC_x ($= 10^{(\text{average}(\log(\text{EC}_x)))}$) and its confidence limits for the battery is calculated as a synthetic result.

3 Results

3.1 Chemical characterisation

Results of chemical analyses are reported in Table 1. Digestate was characterized by alkaline pH, a high conductivity, and high value of COD, phosphate and nitrogen. Most of the nitrogen was present as ammonium (61%).

Moreover the sample was characterised by a deep brown colour.

3.2 Sensitivity of bioassays

Results of ecotoxicity tests, expressed as inhibition percentage of each endpoint are reported in Figure 3. These data were also elaborated calculating the EC₅₀ and its confidence limits (Table 2). The 10 endpoints, recorded by means of the 7 species

representing different positions in the food chain, showed different sensitivity to the sample. The most sensitive organism was *R. subcapitata* with an EC₅₀ of 0.77% and TU of 129.87. Then, *V. fischeri* (30') and *L. minor* (both fronds and biomass development) followed, with EC₅₀ in the range of 1.02-1.77% and TU in the range of 58.82-98.03.

D. magna reported a result of all-or-nothing effect, and the threshold dose was ranging between 3.13% and 1.56%. Thus, these values were reported as the possible range of EC₅₀, and consequently TU of 32.2-62.5.

Another group of tests, *V. fischeri* (15'), *L. sativum* and *A. franciscana*, showed EC₅₀ between 3.03% and 3.90%, and TU between 25.64 and 33.04.

Eventually, *C. sativus* was the lowest sensitive organism, with an EC₅₀ of 14.22% and TU of 7.03.

3.3 Digestate toxicity and risk assessment

According to the synthetic index, all the 10 endpoints were significant; thus, they all contributed to the evaluation of the synthetic index. The EC₅₀ of the battery was 2.33%, with the 95% CL_{low} of 1.88% and 95% CL_{up} 3.15%.

The relative toxicity of the digestate sample ranged from 10% to 100%, for *C. sativus*, *A. franciscana* and *V. fischeri* (30') (Figure 1).

The digestate showed a toxicity score (BTS) of 42.8% that corresponds to a very high toxicity value. Both the total relevance and the consistence of the battery were calculated, too. They were 64% and 100%, respectively. Consequently, the risk score (BRS) of the battery was 55.3% that corresponds to an extremely high risk (Figure 2).

4 Discussion

4.1 Chemical characterisation

Chemical characteristics of a digestate depend basically on the raw material directed towards the digestion process (Provenzano et al., 2011). The analysed sample can be considered representative of pig manure and energy crops digestate for the N content. Actually, it has values of total nitrogen and ammonia in the average of digestate from pig manure and energy crops, which are 2.5-4.5 kg t⁻¹ of total nitrogen and 40-65% of ammonia (Rossi and Mantovi, 2012). On the contrary phosphate is higher than the average of this kind of digestate, which generally is 1-2.2 Kg t⁻¹ (Rossi and Mantovi, 2012). Our digestate showed a slightly higher or comparable nutrient concentration even in comparison with pig slurry digestate in other international studies (De la Torre et al., 2000; Kumar et al., 2010; Park et al., 2010; Albuquerque et al., 2012).

On the contrary, with respect of cattle slurry and raw cheese whey digestate, the pig manure digestate analysed in this study presents a higher ammonium, nitrate, phosphate and TN, but a lower content of COD (Franchino et al., 2013). Digested dairy manure can have a lower phosphate, a higher COD and a nitrogen content comparable with our data (Wang et al., 2010), whereas digested poultry manure showed a lower N:P ratio (Cai et al., 2013; Yetilmezsoy and Sakar, 2008).

4.2 Bioassay sensitivity and possible cause of toxicity

The most sensitive organism for ecotoxicity assessment of digestate was the green alga *R. subcapitata*. At the best of our knowledge, this is the first time that this organism has been used as bioassay to test digestate toxicity, despite this organism is used as a routine test for ecotoxicity assessment (Tigini et al., 2011). Algae are also exploited for biofuel production from digestate (Uggetti et al., 2014). Thus, from an applicative point of

view, this result is of particular interest: actually, if digestate induces an inhibition effect on alga growth, this implies the need of a pretreatment of the digestate or its dilution in order to achieve a good algal growth (Erkelens et al., 2014).

This alga has been indicated as the most sensitive organism also toward textile wastewaters (Novotný et al., 2006; Tigini et al., 2011, Bedoui et al., 2015). This kind of effluents have deep colour in common with digestate and this could be one of the reasons at the base of alga sensitivity. Actually, the sample colour has an inhibitory effect on photosynthetic organisms (Cleuvers and Ratte, 2002).

However, besides the colour, other physical-chemical aspects of the digestate must have a role in the inhibition of photosynthetic organisms, since also *L. minor* and *L. sativum* were sensitive towards the sample. Actually, in these tests the plants are not affected by the sample colour in their photosynthetic activity.

The high ammonium ion concentration could be a key factor in the toxicity of digestate. In landfill leachate with comparable ammonium concentration (2266 mg L⁻¹), it was likely the most important factor of toxicity towards *R. subcapitata*, *L. sativum* and also towards crustaceans (Tigini et al., 2014). Moreover, ammonium is the main cause of toxicity for the alga *Nephroselmis pyriformis* in industrial effluents (Källqvist and Svenson, 2003).

This fact could be at the base also of the high sensitivity of *D. magna*. This crustacean showed an all-or-nothing response, with a nonlinear relationship between dose and effect. *D. magna* showed the same behaviour also towards textile effluents (Bedoui et al., 2015). This indicate that this organism has a sort of resistance that acts as homeostatic compensation of the toxic effect of pollutant, up to a threshold limit that represents the extreme condition for its survival (Calow and Forbes, 2014).

Another factor of toxicity could be the salinity of the sample, which actually had high conductivity. In this case marine organism should be less sensitive with respect to fresh water and soil organisms. Nevertheless, *A. franciscana* and *V. fischeri* showed a high sensitivity towards the sample, too. In particular *V. fischeri* was very sensitive towards the digestate, and the bioluminescence inhibition was proportional to the exposition time. This species was already tested towards pig slurry digestate, showing an EC₅₀ around 6.8% after 15' exposition (Chen et al., 2014), resulting less toxic than the actual pig digestate (EC₅₀ 3.9%). Paying attention to the chemical features of the two samples, the actual digestate presents higher conductivity, COD and phosphate (27 mS cm⁻¹ and 17600 mg L⁻¹, 319 mg L⁻¹, respectively), with respect to the digestate analysed by Chen and colleagues (10 mS cm⁻¹ and 2667 mg L⁻¹, and 152 mg L⁻¹ as TP, respectively). On the contrary, ammonium ion was lower (230 mg L⁻¹ vs 845 mg L⁻¹, respectively). This suggests that ammonium is not the main cause of toxicity towards *V. fischeri*.

Eventually, the less sensitive test was that with *C. sativum*. However, the results indicate still high toxicity, since the EC₅₀ was lower than 25% (Mekki et al., 2008). From literature, it is evident that high concentration of ammonium that characterises animal manure inhibits both the seed germination and the root elongation (Wong et al., 1983). Surprisingly, Gell et al. (2011) found no phytotoxicity in a pig manure digestate but they did not specify the ammonium concentration. The absence of digestate phytotoxicity was recorded also by other authors, but the conditions were only partially comparable with the present work. Actually, some studies were performed in vivo (Różyło et al., 2015), other applied different exposition periods (Alvarenga et al., 2015) or other kinds of digestate (Massaccesi et al., 2013). In a most recent study, the use of

proper concentrations of digestate as a biofertiliser is encouraged, since it causes biostimulation under 20% dose (Pivato et al., 2015).

4.3 Synthetic index and risk assessment for the evaluation of digestate exploitation

The applied synthetic index for toxicity and risk evaluation allows to describe a valid forecast of the environmental impact of the considered samples. This method attributes different weights to the endpoints on the base of an expert judgment. Thus the endpoints affect with different weight to the toxicity score attributed to the battery. On the basis of this elaboration, the impact of the tests with *L. sativum*, *C. sativus*, and *L. minor* increased, because the root development is characterised by high weight (= 4), soon after the bioluminescence (= 5), and before the algal reproduction (= 3), and the crustaceans behaviour (= 1). In the light of the possible use of digestates in agriculture, this evaluation of phytotoxicity tests acquires an additional importance.

The high toxicity and the extremely high risk associated to the sample indicate a serious danger for the environment associated to pig slurry digestate. This datum is alarming and confirms what underlined by Nkoa (2014) about the danger of digested animal manures. Actually, he observed that anaerobic digestates have a higher potential to harm the environment and human health than undigested animal manures and slurries, on account of their higher NH₃ emission potential.

Despite the N content in digestate, basically consisting of ammonium, can be easily up-taken by plants, its high toxicity effect can be explicated for many months (Różyło et al., 2015). Thus, the products of anaerobic digestion must satisfy certain level of stability and hygiene in order to fulfil sustainability criteria of reuse in agriculture, and this could be achieved by digestate dilution or pre-treatment (Albuquerque et al., 2012,

Chen et al., 2014). This is the case of the actual digestate. An algal pretreatment aimed to biofuel production could represent a solution. Actually, besides allowing the achievement of the needed quality, it could lower the impact of the overall producing chain. However, on account of the high toxicity towards algae, a feasibility study should be performed. In alternative (or in addition) a pre-treatment with fungal biomasses could be a possible tool to reduce the toxicity of recalcitrant molecules or the colour, which are the two main cause of toxicity of digestate towards algae. Actually, fungal biomasses are able to decolourise very toxic wastewater coupling a decrease of the toxicity (Anastasi et al., 2011; Spina et al., 2014).

5. Conclusions

In this work, the toxicity of a pig slurry digestate was assessed through 7 ecotoxicity tests and considering 10 different endpoints. Besides, a synthetic index was used to summarise the obtained results for the environmental risk evaluation, in order to consider the opportunity to use directly this kind of digestates in agriculture or to introduce an additional treatment. All the organisms were sensitive to digestate toxicity. The chemical features at the base of this toxicity seem to be the high content of ammonium, salinity, COD, phosphate and colour. A more deep chemical characterisation (organic contaminants, metals, phenols) could give additional information about the cause of this high toxicity. According to the synthetic index the digestate was very toxic and was associated to an extremely high environmental risk. A digestate pretreatment is needed to reduce its toxicity and environmental impact.

Acknowledgement: This work was supported by University of Turin. This work was

partially funded by Master dei Talenti della Società Civile della Fondazione Giovanni Goria e della Fondazione CRT and by Ministero dell'Istruzione, dell'Università e della Ricerca (MIUR) with the FIRB project RBFR13V3CH_002 with the title "In situ bioaugmentation to exploit the combination of fungi and bacteria for recalcitrant compounds removal". A special thanks goes to Dr. Rocco Mussat Sartor, to Mr. Pietro Giansanti of Arpa Piemonte, for the *Daphnia magna* test, and to Dr. Renato Baudo and Commissione UNICHIM Qualità dell'acqua, Gruppo di Lavoro Metodi Biologici, Sottogruppo Acque salate/salmastre e sedimenti, for allowing us to use the synthetic index for ecotoxicological risk assessment.

References

1. Albuquerque JA, de la Fuente C, Ferrer-Costa A, Carrasco L, Cegarra J, Abad M, Bernal MP. Assessment of the fertilizer potential of digestates from farm and agroindustrial residues. *Biomass and Bioenergy* 2012; 40:181-189.
2. Alvarenga P, Mourinha C, Farto M, Santos T, Palma P, Sengo J, Morais M-C, Cunha-Queda C. Sewage sludge, compost and other representative organic wastes as agricultural soil amendments: Benefits *versus* limiting factors. *St Manage* 2015; 40:44-52.
3. Anastasi A, Parato B, Spina F, Tigini V, Prigione V, Varese GC. Decolourisation and detoxification in the fungal treatment of textile wastewaters from dyeing processes. *N Biotechnol* 2011; 29:38-45.
4. Baronchelli A. Lo stato dell'arte del biogas. Book of Proceedings. Biogas Italy, dalla terra per la Terra, 2015, 12-13 February 2015 Rimini, Italy.
5. Bedoui A, Tigini V, Ghedira K, Varese GC, Chekir Ghedira L. Evaluation of an

- eventual ecotoxicity induced by textile effluents using a battery of biotests. *Environ Sci Pollut Res Int* 2015; 22:16700-8.
6. Cai T, Park SY, Li Y. Nutrient recovery from wastewater streams by microalgae: status and prospects. *Renew. Sust Energ Rev* 2013; 19:360-369.
 7. Calow P, Forbes VE. *Ecotoxicology*. eLS. 2014.
 8. Canna-Michaelidou S, Christodoulidou M. Development and implementation of indices for the quality of treated effluent. *Int J Environ Pollut* 2008; 33:72-81.
 9. Casieri L, Varese GC, Anastasi A, Prigione V, Svobodova K, Marchisio VF, Novotny C. Decolorization and detoxication of reactive industrial dyes by immobilized fungi *Trametes pubescens* and *Pleurotus ostreatus*. *Folia Microbiol* 2008; 53:44-52.
 10. Chen W, Cai Q, Zhao Y, Zheng G, Liang Y. Toxicity Evaluation of Pig Slurry Using Luminescent Bacteria and Zebrafish. *Int J Environ Res Public Health* 2014; 11:6856-6870.
 11. Cleuvers M, Ratte HT. The importance of light intensity in algal tests with coloured substances. *Water Res* 2002; 3:2173-2178.
 12. Costan G, Bermingham N, Blaise C, Ferard JF. Potential ecotoxic effects probe (PEEP): a novel index to assess and compare the toxic potential of industrial effluents. *Environ Toxicol Water Qual* 1992; 8:115-140.
 13. De la Torre AI, Jiménez JA, Carballo M, Fernandez C, Roset J, Munõz MJ. Ecotoxicological evaluation of pig slurry. *Chemosphere* 2000; 41:1629-1635.
 14. Erkelens M, Ward AJ, Ball AS, Lewis DM. Microalgae digestate effluent as a growth medium for *Tetraselmis* sp in the production of biofuels. *Biores Technol* 2014; 167:81-86.

15. Franchino M, Comino E, Bona F, Riggio VA. Growth of three microalgae strains and nutrient removal from an agro-zootechnical digestate. *Chemosphere* 2013; 92:738-44.
16. Gell K, Groenigen JV, Luz M. Residues of bioenergy production chains as soil amendments: Immediate and temporal phytotoxicity. *J Hazard Mater* 2011; 186:2017-2025.
17. Hartwell SI. Demonstration of a toxicological risk ranking method to correlate measures of ambient toxicity and fish community diversity. *Environ Toxicol Chem* 1997; 16:361-371.
18. Holm-Nielsen JB, Al Seadib T, Oleskowicz-Popielc P. The future of anaerobic digestion and biogas utilization. *Biores Technol* 2009; 100:5478–5484.
19. Källqvist T, Svenson A. Assessment of ammonia toxicity in tests with the microalga, *Nephroselmis pyriformis*, Chlorophyta. *Water Res* 2003; 37:477-484.
20. Kumar MS, Miao ZH, Wyatt SK. Influence of nutrient loads, feeding frequency and inoculum source on growth of *Chlorella vulgaris* in digested piggery effluent culture medium. *Bioresour Technol* 2010; 101:6012-6018.
21. Massaccesi L, Sordi A, Micale C, Cucina M, Zadra C, Di Maria F, Gigliotti G. Chemical characterisation of percolate and digestate during the hybrid solid anaerobic digestion batch process. *Process Biochem* 2013;48:1361–1367.
22. Mekki A, Dhouib A, Feki F, Sayadi S. Assessment of toxicity of the untreated and treated olive mill wastewaters and soil irrigated by using microbiotests. *Ecotoxicol. Environ. Saf.* 2008; 69:488–495.
23. Möller K, Stinner W. Effects of organic wastes digestion for biogas production on mineral nutrient availability of biogas effluents. *Nutrient Cycling in*

- Agroecosystems 2010; 87:395-413
24. Nkoa R. Agricultural benefits and environmental risks of soil fertilization with anaerobic digestates: a review. *Agron Sustainable Dev* 2014; 34:473-492.
 25. Novotný C, Dias N, Kapanen A, Malachová K, Vándrovcová M, Itävaara M, Lima N. Comparative use of bacterial, algal and protozoan tests to study toxicity of azo- and anthraquinone dyes. *Chemosphere* 2006; 63:1436-1442.
 26. Park J, Jin HF, Lim BR, Park KY, Lee K. Ammonia removal from anaerobic digestion of livestock waste using green alga *Scenedesmus* sp. *Bioresour Technol* 2010; 101:8649-8657.
 27. Persoone G, Marsalek B, Blinova I, Törökne A, Zarina D, Manusadzianas L, Nalecz-Jawecki G, Tofan L, Stepanova N, Tothova L, Kolar B. A Practical and User-Friendly Toxicity Classification System with Microbiotests for Natural Waters and Wastewaters. *Environ. Toxicol.* 2003; 18:395-402.
 28. Pivato A, Vanin S, Raga R, Lavagnolo MC, Barausse A, Rieple A, Laurent A, Cossu R. Use of digestate from a decentralized on-farm biogas plant as fertilizer in soils: An ecotoxicological study for future indicators in risk and life cycle assessment. *Waste Manag.* 2015 Dec 23. pii: S0956-053X(15)30243-9. doi: 10.1016/j.wasman.2015.12.009. [Epub ahead of print].
 29. Provenzano MR, Iannuzzi G, Fabbri C, Senesi N. Qualitative Characterization and Differentiation of Digestates from Different Biowastes Using FTIR and Fluorescence Spectroscopies. *Journal of Environmental Protection* 2011; 2:83-89.
 30. Rossi L, Mantovi P. *Conoscere per comprendere* n° 4, p 1. Ed: Centro Ricerche Produzioni Animali– CRPA. 2012.

31. Różyło K, Oleszczuk P, Joško I, Kraska P, Kwiecińska-Poppe E, Andruszczak S. An ecotoxicological evaluation of soil fertilized with biogas residues or mining waste. *Environ Sci Pollut Res* 2015; 22:7833–7842.
32. Spina F, Romagnolo A, Prigione V, Tigini V, Varese GC. A Scaling-up Issue: The Optimal Bioreactor Configuration for Effective Fungal Treatment of Textile Wastewaters. *Chemical Engineering Transactions* 2014; 38:37-42.
33. Tigini V, Giansanti P, Mangiavillano A, Pannocchia A, Varese GC. Evaluation of toxicity, genotoxicity and environmental risk of simulated textile and tannery wastewaters with a battery of biotests. *Ecotoxicol Environ Saf* 2011; 74:866-73.
34. Tigini V, Prigione V, Varese GC. Mycological and ecotoxicological characterisation of landfill leachate before and after traditional treatments. *Sci Total Environ* 2014; 487:335-41
35. Uggetti E, Sialve B, Trably E, Steyer JP. Integrating microalgae production with anaerobic digestion: a biorefinery approach. *Biofuels, Bioproducts and Biorefining* 2014; 8:516–529.
36. Baudo R, Faimali M, Onorati F, Pellegrini David. Batterie di saggi ecotossicologici per sedimenti di acque salmastre e superficiali – I Manuali di Ecotossicologia, ISPRA Manuli e Linee Guida 67/2011, ISBN: 978-88-448-0498-5.
37. Wang L, Li Y, Chen P, Min M, Chen Y, Zhu J, Ruan RR. Anaerobic digested dairy manure as a nutrient supplement for cultivation of oil-rich green microalgae *Chlorella* sp. *Bioresour Technol* 2010; 101:2623-28.

38. Wong MH, Cheung YH, Cheung CL. The effects of ammonia and ethylene oxide in animal manure and sewage sludge on the seed germination and root elongation of *Brassica parachinensis*. *Environ Poll Ser A* 1983; 30:109–123.
39. Yetilmezsoy K, Sakar S. Improvement of COD and color removal from UASB treated poultry manure wastewater using Fenton's oxidation. *J Hazard Mater* 2008; 151:547-558.
40. Zhang S, Bi XT, Clift R. Life cycle analysis of a biogas-centred integrated dairy farm-greenhouse system in British Columbia. *Process Safety and Environmental Protection* 2015; 9:18–30.