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1 **Livestock waste treatment systems**
2
3 **for environmental quality, food safety, and sustainability.**
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6
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23 **Abstract**
24

25 The intensification of livestock operations has benefited production efficiency but has introduced major
26 environmental issues, becoming a concern in both developed and developing countries. The aim of this
27 paper is primarily to address the impact of the livestock sector on environmental pollution (ammonia,
28 greenhouse gases and pathogens), evaluate the related health risks and, subsequently, assess the potential
29 role of waste treatment systems in attenuating these environmental and health issues. This paper is a
30 collection of data pertaining to world trends in livestock production, since the mid 1990's and intensive
31 livestock farming practices along with their impact on: water pollution by nitrates and through
32 eutrophication; air pollution, particularly ammonia and greenhouse gases emissions, and soil pollution
33 because of nutrient accumulation. Finally, this paper examines some of the benefits of treating livestock
34 manures, issues related to the adoption of treatment systems by livestock operations and current as well as
35 past technological developments.
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49 *Key words* : livestock wastes, environmental risk, treatment.
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54 **1. Introduction**
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56 As an integral part of the traditional farming system, livestock was crucial in contributing to the
57 sustainability of agricultural systems by: (i) utilizing crop residues and other feeds which were not used
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1 by humans and by converting them into milk and meat; (ii) providing a soil amendment (manure) which
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3 recycles about 70% of the feed minerals which are not digested and otherwise would be lost, and; (iii) for
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5 the poorest regions of the world, providing traction for cultivation, supply for energy production or home
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7 construction (dried cowpat). However, the price of goods produce in farm operations has not increased
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9 since the late 1960's, while all other costs have increased by more than 10 times. This price trend has
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11 forced the mixed farming system into intensive livestock operations, and in turn, greatly modified the fine
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13 and well balanced cycle of using manure nutrients to replenish the soil with minerals. The animals are fed
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15 directly by cereals feed from which a high proportion (not assimilated by animals) is finally released into
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17 the environment with or without prior treatment. It results in global losses of nutrients at several levels:
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19 concurrence with the use of cereals in human food, low efficiency of cereals uptake by animal, cost of
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21 manure treatment before spreading when it is necessary and negative impact on the environment in areas
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23 of animal concentration. Modern intensive livestock operations exert considerable environmental impacts,
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25 a subject of increasing concern for developed countries but also for developing countries with a lack of
26
27 policy and strict rules requiring environmental protection.

28
29 The future of livestock farming is therefore at the heart of a serious debate concerned with the critical
30
31 issue of the global food crisis. Three main challenges are faced :

- 32
33 1. Policy perspectives and risk prospects associated with the intensification of livestock production,
34
35 particularly within the fast growing economy of developing countries;
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38 2. Environmental issues linked with the over-use of natural resources and the subsequent depletion
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40 of their ability to regenerate; these environmental issues pertain to air pollution such as
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42 greenhouse gases emissions, soil pollution through nutrients build-up and saturation and water
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44 quality;
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47 3. Technological changes inducing the "accelerated" implementation of well-known treatment
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49 systems in developed countries and the adaptation or technological transfer of these solutions to
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51 developing countries.

52 The Green Revolution which emerged after World War II was driven by supply, and inputs, such as
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54 fertilisers, pesticides and irrigation water, and better genetic potential which brought tremendous
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56 improvements in production efficiency. At the same time, the low prices for food produce at the farm
57
58 assured an affordable food supply accessible to most, particularly in developed countries (Hodges, 2005).

1 Along with this trend of providing low cost and plentiful food supply, the end of the twenty century was
2 characterised by the so-called “livestock revolution”. This revolution was mostly driven by a strong
3 demand for food from animal origin, still at a low farm cost. It results a change in diet for billions of
4 people, as well as an important population growth (Gerber et al., 2005, Gerber & Steinfeld, 2006). The
5 pressure to maintain low prices for produce at the farm widened the gap between rural and urban
6 economies, leading to greater urbanization and income growth in developing countries (Adhikari et al.,
7 2006). In speaking of food, the entire human life is impacted, as “food is life” (Hodges, 2005).
8 Nevertheless, the production of organic residues is inherent to the livestock farming activity, and among
9 these residues, animal manures are by far the more important stream.

10 In Europe, the move from mixed arable-livestock farming to greater specialization has had a major
11 adverse environmental effect. The environmental effects of different livestock manure systems have been
12 the subject of scrutiny and a number of reviews and reports were produced (Nicholson et al., 2002;
13 Voermans et al. 1994; Martinez & Le Bozec, 2000; Hooda et al., 2000; Leinweber et al., 1997).

14 Among these, the poor management of livestock effluents has directly impacted the nitrogen load in soil
15 and the subsequent transfer to surface and groundwater resources. The European community first
16 introduced nitrate regulations in 1991 to address this issue and more recently the EU-27 introduced the
17 water framework regulation aimed at improving water quality. In addition and for the last 30 years, the
18 gaseous emissions of ammonia nitrogen is a major topic of concern in Europe, first because it represents a
19 loss of valuable nutrient and second because this gas exerts negative effects such as eutrophication and
20 acid rains. The European community is presently applying a regulation pertaining to ceilings in ammonia
21 emissions.

22 Unlike the current approach which tends to install manure treatment processes as a constraint at the end of
23 a chain of livestock production, a most holistic, environmentally safer and reasonable choice would be to
24 define the types of livestock and manure management to be developed in light of the remediation
25 capacities of their environment. In other words, think about manure management before or at least at the
26 same time as the animal production mode itself. Thus, according to the needs of the land, the treatment
27 could sometimes be unnecessary, sometimes necessary or optional, but always seen as an alternative to
28 further transform manure in co-products or energy. There exist solutions which, at the moment, are
29 mainly focuses on the elimination of organic matter and nitrogen. Other solutions to the excess manure

1 problem need to be created, as for energy production, recycling of phosphorus or greenhouse gases
2
3 emissions reduction.
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7 Treatment technologies can play a role in the management of livestock manure by providing a more
8
9 flexible approach to land spreading and by resolving specific problems such as malodours or ammonia
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11 emissions. Such treatments are based on biological and physical processes, with the possible use of
12
13 chemical additives. The technologies already used by large farms are separation and composting,
14
15 anaerobic digestion and aeration. The challenge for many countries is how to implement such
16
17 technologies both at a wider scale and economically. In countries outside Europe and North America, the
18
19 adaptation and development of specific treatment systems must deal with regional constraints and cultural
20
21 peculiarities. For examples, in Japan and South-East Asia, cultural concerns prescribe the use of manure
22
23 to fertilize soils and climatic conditions have a major impact on the selection of the treatment, the dilution
24
25 of the waste and the potential for runoff (Burton & Martinez, 2008).
26

27 The objective of this paper is therefore to assess and review the potential role of treatment systems in
28
29 dealing with surging environmental pollution issues. This paper examines the potential use of manure
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31 biomass within a renewable context, and in terms of reducing greenhouse gases emissions.
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35 **2. The future of animal production**

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39 ***2.1. Global production, general trends and perspectives***

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42 The current world population is unevenly distributed economically and socially. Five billion people live
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44 in the “developing world” whereas the “developed world”, sometimes called “The West”, represents less
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46 than one billion people.

47 As the economy of these countries improves, their demand for animal products is likely to increase,
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49 along with a greater disparity between rural and urban economies resulting in a greater urban population
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51 growth. The disparity between rural and urban economies results from the fact that the price of farm
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53 products have not increased since the early 1970’s, while all other costs have. As a result of a greater
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55 income, a diet richer in meat, milk and eggs can improve human nutrition. In contrast to the developed
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57 world where many people eat too much animal products, most people in developing countries eat too
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1 little. Since 1960, the world population has doubled while animal numbers have increased by 50 % for
2 ruminants, 200 % for pork and 280 % for poultry. From the global distribution of major animal types
3 (Figure 1), cattle numbers are more evenly distributed than those for swine. Asia still contributes about
4 one third of the cattle production and more than half of the swine production. For swine production,
5 Europe' share is about 20%. The regional concentration of pigs and pig meat production shows that the
6 ten largest producers account for 74% to the global pig stock (Windhorst, 2006).
7
8 In terms of meat, pork accounts for the largest proportion at 80 million tons per year compared to 50
9 million tons each for cattle and poultry. The total annual global meat production is estimated between 200
10 and 230 millions tons. Almost half of the world's chicken population is concentrated in Asia. The
11 regional concentration in chicken meat and egg production is particularly high: more than 64% of the
12 global chicken meat production is concentrated in 10 leading countries, almost half coming from the
13 USA, China and Brazil.

14
15 The trends in world population [Delgado et al. (1999) Ehui et al. (1998)] and the concurrent growth in
16 demand for livestock products suggest that by 2020, annual production will have to grow by another 200
17 billions litres of milk and 100 millions tons of meat (Table 1). Such a large increase will require more
18 than the simple adaptation of current livestock farming practices as they exist in Europe and North
19 America.

2.2. Major nutrient flows

20
21 The importance of livestock production for every person on the planet is illustrated by the increasing
22 demand for meat, eggs and dairy products for at least the developing countries (Faye & Alary, 2001).
23 Also, livestock production has an impact on the global flow of nutrients, particularly for N, an important
24 nutrient for agriculture and the environment. Table 2 illustrates the respective needs for N between the
25 human population and the global livestock farm system. The global N intake by animals is estimated as
26 110 million tons/yr while the global N excretion by animals is estimated at 100 million tons, implying a
27 10% efficiency in N use (Bouwman & Booij, 1998). This illustrates the strategic importance of
28 optimizing the recycling of manures and to use them as a resource and an organic fertilizer. The global
29 swine population produces roughly 1.7 billion tons/yr of liquid manure which can, at an application rate
30 of 40 tons/ha, fertilize 45 million ha of land annually (Choudhary et al., 1996).

1 In a paper revisiting the agronomic benefits of manure, Schröder (2005) described agriculture as a chain
2 of activities transferring nutrients in a cyclic way: (1) from the soil; (2) via the crop; (3) via the animals
3 and humans, and; (4) via manure back to the soil again. Each step is characterized by an efficiency value
4 or a ratio of outputs and inputs, which gives an indication of the transfer efficiency for N (Table 3),
5 reinforcing the fact that the introduction of mineral fertilizers has significantly disturbed the balance
6 between crop and animal production. The question is therefore how to restore such integrity without
7 going back to historical times and ancient practices, but within a modern and sustainable agricultural
8 system.

9 This problem is even more crucial for phosphorus. While nitrogen can be artificially synthesized from
10 natural gas, phosphorus is a non-renewable resource extracted from soil, which is expected to be depleted.
11 Since mineral fertilisers and animal feeds account for approximately 80% and 5% of phosphates used
12 worldwide, it is clear that depletion of phosphorus production will impact animal production and manure
13 recycling within the next decades.

14 **3. Environmental impact of Livestock Waste**

15 ***3.1. Soil pollution***

16 Animal manures were regarded historically as beneficial soil amendments rich in nutrients and organic
17 matter that also sustain the soil physical properties such as structure and moisture retention. Farmers have
18 traditionally applied these organic fertilisers for the long term benefit of their soils. Manure helps
19 stabilization of soil aggregates preventing erosion, it improves soil structure promoting moisture retention
20 and it even may correct drainage problems in wet areas.

21 Repeated soil over-applications of manure, above crop requirements, lead to the accumulation of not only
22 macro nutrients such as N, P and K, but also heavy metals particularly Cu and Zn, impacting animal
23 health through grazing and crop feeding (Lopez Alonso et al., 2000). The main consequence of nutrient
24 overloaded soils is related to the interaction between soils and its water and air fractions. Water pollution
25 occurs mainly through the leaching of nitrates applied in excess of plant uptake, while air pollution is the
26 consequence of complex processes including nitrification/denitrification and also the breakdown and
27 transformation of organic matter in soils (Figure 2). Soils plays therefore a major role in the retention,
28

1 transformation and release of gaseous or soluble compounds. In some cases, like for methane, soils can
2
3 act as sink, through oxidation processes.
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5 6 7 **3.2. Water pollution**

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9 Water pollution by animal production is often caused by the leaching and runoff of minerals from the soil
10
11 or by direct disposal of wastes into watercourses. Animal manure nutrients in excess of crop uptake,
12
13 accumulate and even saturate soils. At saturation, nutrients are lost to either surface or ground waters.
14

15 Nitrogen and phosphorus are the two nutrients of special agricultural importance with the greatest
16
17 potential to create water pollution. Although not an issue presently, potassium (K) will be another
18
19 problem in the near future as the application of manures based on the plant uptake of P generally leads to
20
21 the surplus application of this mineral (Béline *et al.*, 2003). Both N and P surplus can pollute surface
22
23 waters through runoff while limited amounts are immobilised by the soil organic matter. Free ammonia,
24
25 rather than the ammonium salt, has a greater impact on water systems because of its toxicity to many fish
26
27 species. For instance, Salmon, an ammonia sensitive fish, is affected by 5 mg/L of ammonia.
28

29 While documenting the water quality concerns in livestock areas, Hooda et al. (2000) specifically
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31 illustrated the problem and concluded that there is a general uncoupling of nutrient cycles, and problems
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33 related to nutrient loss are either short-term direct losses or long-term, related to accumulated nutrient
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35 surpluses.
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37 38 39 **3.3. Air pollution**

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41 Animal production has been identified as a major contributor to atmospheric pollution (Pain, 1999). The
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43 air in livestock housing contains over a hundred gaseous compounds released into the atmosphere by the
44
45 ventilation system. Of these gases, odorous substances and especially ammonia have been the main
46
47 concerns from an environmental perspective (Hartung and Phillips, 1994). The largest proportion of the
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49 gases arising from animal husbandry is produced from freshly deposited or stored faeces and urine,
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51 through microbial activity.
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53 54 55 **3.3.1 Emissions of ammonia**

1 The estimated global emission of ammonia (NH₃) for 1990 is in the range of 54 million tons NH₃-N/yr, of
2 which 43 million tons NH₃-N/yr (80%) stems from anthropogenic sources. The major anthropogenic
3 sources include excreta from domestic animals (50%) and use of synthetic N fertilisers (25%) (Olivier et
4 al., 1998). In 1990, anthropogenic ammonia emissions to the atmosphere in Western Europe were
5 estimated at 2.8 - 5.2 million tons NH₃-N/yr. Manure from farm animals was the principal source
6 (ECETOC, 1994) and their emissions were damaging the environment through soil acidification and
7 eutrophication. In addition, these emissions constitute an important loss of valuable N fertiliser.

8
9 The loss of ammonia to the atmosphere occurs from animal housing, manure storage facilities, and from
10 the application of manure to land. Approximately 50% of the ammonia emissions from swine production
11 originate from the shelter and the slurry storage, while the other 50% is emitted following land
12 application. The most important factors influencing ammonia emissions are the concentration of ammonia
13 nitrogen in the slurry, the emitting surface, the pH of the slurry, the air velocity over the slurry and the
14 slurry temperature (Van der Peet-Schwering et al., 1999). In animal house, NH₃ is a health risk to animal
15 and man, because long term exposure to NH₃ combined with dust can cause severe lung diseases (Seedorf
16 et Hartung, 1999). Furthermore, high concentration of NH₃ may reduce animal performance.

17 In Europe and over the past decade, ammonia emissions has been a concern because of high deposition
18 rates on land and over water surface, causing long-term damage to sensitive natural and semi-natural
19 ecosystems. Transported over long distances in the atmosphere, ammonia is both a national and
20 international problem. EU Member States are signatories of international agreements to limit emissions.
21 The UNECE “Protocol to Abate Acidification, Eutrophication and Ground-level Ozone” (also known as
22 Gothenburg Protocol) was signed in 1999 under the 1979 Geneva “Convention on Long-range
23 Transboundary Air Pollution” and entered into force on 17 May 2005 (Mallard, 2006). The main
24 signatories are the European Community, the European countries, the Unites States of America and the
25 Russian Federation, this last one having not ratified the protocol yet. The protocol fixes national annual
26 emissions targets for different gases: SO₂, NO_x, NH₃ and volatile organic components (VOC), to be
27 reached by 2010.

28 On this basis, the 2001 NEC directive (directive 2001/81/EC of the European Parliament and of the
29 Council) fixes national emissions ceilings for the same different gases, to be reached for the same year
30 and, for ammonia, at the same level as the Gothenburg Protocol. The NEC directive is currently in the

1 process of implementation. Member States had to build national programmes (by October 2002), to show
2 how they were going to meet the national emission ceilings by 2010 (this programmes were updated and
3 revised in 2006).
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6 7 8 9 *3.3.2 Methane and nitrous oxide emissions and climatic change*

10 The current predictions of climatic disruption caused by human activities include one scenario where
11 there is a possible temperature increase of up to 4°C within the next 40 to 75 yr. With respect to
12 agriculture, such a climatic change might result in the drying up of currently fertile large land surfaces.
13 Cold regions such as the tundra of the northern hemisphere will not necessarily become suitable for crop
14 production. More specifically, there is no reason to assume that agriculture will adapt quickly enough to
15 any climatic change resulting from the global “warming” trend.
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18 Methane and nitrous oxide are major greenhouse gases implicated in the global warming phenomenon.
19 They are also involved in the photochemical reactions in the troposphere that determine concentrations of
20 ozone and hydroxyl radicals. Hydroxyl radicals are termed the ‘detergents of the atmosphere’ because
21 they are responsible for the removal of almost all gases that are produced by natural processes and human
22 activities.
23

24 The Intergovernmental Panel on Climate Change (IPCC) calculated that 1 kg of CH₄ has 63 times the
25 warming effect of 1 kg of CO₂, over a period of 20 years following the gas release (calculated over one
26 hundred years, the warming effect of methane is 21 to 23 times the warming effect of CO₂). The average
27 atmospheric CH₄ concentration is currently 1.7 ppmv (parts per million by volume) or approximately,
28 depending on temperature and pressure, 1.2 micrograms /m³ of air. The concentration started to increase
29 from a baseline value of about 0.8 ppmv in pre-industrial times 200-300 years ago and is currently
30 increasing at a rate of about 1 %/yr. The increased abundance of CH₄ will have important impacts on
31 global climate changes, and on the tropospheric (ground-based) and stratospheric ozone layers. Methane
32 is estimated to contribute about 20 % of the expected global warming trend, second only to CO₂. Nitrous
33 oxide has a global warming effect ten times that of CH₄ and hence its lower concentration in the
34 stratosphere still equates that of CH₄. For both gases, the largest single source of anthropogenic emission
35 is agriculture (Duxbury, 1994) (Table 4). In case of ruminant production, the majority of methane
36 emission is from enteric activity that cannot be reduced in a short time period, or may not be reduced at
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1 all. On the opposite, in case of pig production, 89% of methane emissions are due to manure management
2 storage and could be reduced by changing manure management practices or biogas collection (Table 5).
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4 A recent FAO report (2006) estimates that 35% of global greenhouse-gas emissions deriving from
5 agriculture and land use comes from livestock production. This sector accounts for about 18% of global
6 greenhouse-gas emissions, consisting in around 9% of global emissions of carbon dioxide, plus 35-40%
7 of methane emissions and 65% of nitrous oxide.
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14 *3.3.3 Dust and other particles*

15 Dust has not been reported as an important environmental issue in the surroundings of farms. Inside the
16 animal house however, it is known to be a contaminant that can affect both the respiration of the animals
17 and the farmer (Copeland, 2006; Anderson et al., 2003).
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23 The highest concentration of airborne dust, bacteria, fungi and endotoxins can be found within poultry
24 shelters but high values also occur in swine shelters. Table 6 gives an overview of the different bio-
25 aerosols components found in livestock shelters. Exposures to bio-aerosols in animal shelters are
26 associated with a wide range of adverse health effects, including infectious and non-infectious diseases.
27 Endotoxins are particularly harmful since they can induce allergic reactions of the respiratory system that
28 can become chronic.
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37 *3.4. Disease risks and health issues*

38 Livestock waste may contain various pathogenic microorganisms (bacteria, viruses or parasites) that can
39 present a sanitary risk during their subsequent spreading on agricultural land. Whilst some pathogens are
40 obligate parasites and are of limited concern, others can survive in the environment for long period (as
41 viable cells or more often as cyst or spore). Pathogens survival and movement through soil depends upon
42 many factors like soil type, water content and pH; microorganisms surface properties and motility and
43 environmental factors like temperature, plants and micro- and mesofaunal activity (Abu-Ashour et al.,
44 1994).
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53 Hygiene concerns resulted from a series of food scares resulting from the microbiological contamination
54 of agricultural food products such as Salmonella, E-coli, campylobacter and also BSE (Bovine
55 Spongiform Encephalopathy). Examples of notable outbreaks of diseases affecting even livestock are the
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1 foot and mouth disease, the classical swine fever and more recently, the avian influenza which
2 exemplifies a possible zoonotic disease further endangering the general public. Manure disposal will
3 certainly be an issue during any of these outbreaks. De-contamination will be conducted either by the
4 addition of proven disinfectants or, for very large quantities, extended storage for the long term demise of
5 the specific pathogen.
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11 Few incidences of water contamination by zoonoses were reported but each tends to be a very serious
12 event with human fatalities (Guan and Holley, 2003). Accordingly, additional restrictions were imposed
13 on where and how manures may be land spread but no treatment was mandatory when aeration, especially
14 at temperatures over 50 °C, anaerobic digestion, the use of disinfectants and prolonged isolated storage
15 can be very effective (Burton and Turner, 2003) but without total elimination. Thermal treatments
16 constitute a more rigorous and reliable approach (Turner and Burton, 1997) although less costly than
17 originally expected, but the use of such technology is still limited to specific areas of high risks.
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During non epidemic periods, drastic treatment is not required for manure that is simply stored for 4 to 6 months before spreading. This storage allows the number of pathogens possibly present in manure to decrease but not to totally disappear. In the case of pig manure, the antimicrobial effectiveness of 5 biological treatments of manure has been evaluated by the enumeration of 3 treatment indicators (enterococci, *Escherichia coli* and *Clostridium perfringens*) and the detection of two pathogenic bacteria (*Salmonella* and *Listeria monocytogenes*) (Pourcher et al, 2007). The studied treatments consisted either of a simple storage of the raw manure, or of more complex treatments designed for the removal of nitrogen and phosphorus (biological treatment with or without physical separation of manure). The results underlined the existence of a potential risk of spreading *Salmonella* which were detected in 60% of the 17 raw manures and in 20% of the 10 treated manures analysed. The N removal treatment resulted in a decrease in *E coli* and enterococci concentrations, but was not however sufficient to completely eliminate the pathogenic bacteria and it had no effect on the spores of *C perfringens*. Indeed only the composted manure separated solid and the treated manure separated liquid from the pond appeared free of (or undetected) pathogens.

As a consequence, spreading of raw or even stored untreated manure presents a danger even if the actual risk of contamination has not been evaluated. It has been observed that spreading resulted in a transient increase in number of pathogenic microorganisms in soil (Gessel *et al.*, 2004). The health risk increases

1 when manure is spread on soil where certain crops (e.g. salads, fruit and some vegetables) that are not
2 intended to be cooked are grown (Nicholson *et al.*, 2005). Recently, the European regulation has been
3 strengthened concerning the hygienic quality of recycled animal by-products like composted raw manure
4 separated solids (regulation n° 1774/2002). It requires animal by-products to contain less than 5×10^3 *E.*
5 *coli* or enterococci per g of product and the absence of *Salmonella* in 25g of product.
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9 From a disease perspective, the biggest impact of manure management is likely that of food quality,
10 rather than from governments regulations. Farm produce quality is impacted by the method of applying
11 the manure on crops and the most vulnerable crops are leaf vegetables eaten raw. Because such
12 application is forbidden by law, manure land application as part of a farm cycle may become increasingly
13 difficult and the consequence may further encourage the treatment of manure at the farm.
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23 **4. Treatment systems for livestock wastes: assessment of their future role**

24 **4.1. Technological options**

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27 Livestock operations can benefit from the adoption of better management methods that simultaneously
28 improve production efficiency. Inevitably, an efficient waste collection and storage system is required
29 before land disposal. Many European and North American farms have already adopted equipment or
30 techniques simplifying this operation such as mixers and separators which reduce blockage problems and
31 facilitate transportation. In some cases, these measures can minimize environmental impacts, because
32 they result in a more uniform land application of manure nutrients. In a few cases, financial rewards such
33 as a premium price for electricity generated from the anaerobic digestion of organic wastes has
34 encouraged the adoption of treatment technology. Otherwise, the benefit gained from manure treatment
35 technologies generally do not cover their investment cost and operation complexity, resulting in most
36 farms in Europe and North America responding only under the pressure of environmental legislation.
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49 As opposed to direct land application, the treatment of manure implies processing technology changing its
50 physical or chemical characteristics. This may be brought about by physical, chemical, mechanical or
51 biological processes or a combination of these. A wide range of equipment and systems are potentially
52 available in Europe and North America to treat manures (Burton & Turner, 2003) but few were adopted
53 on a large scale because of :
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- heavy investment and operating costs without an equivalent return;
- their complexity and impracticality for the livestock operator;
- poor adaptation for the livestock farm;
- further environmental problems arising from the process, such as odours.

Further development may yet reduce these constraints, but for the present, Europe and North America livestock operation have adopted the following practical options for manure treatment :

- Composting systems or related technologies producing a useful solid product;
- Biological systems for liquids that effectively breakdown some of the organic load;
- Separation systems removing solids for the clarification and/or concentration of manure nutrients.

Storage, mixing and application systems by themselves do not constitute a manure treatment but they are crucial in minimizing the environmental impact. Although certain chemicals such as lime or flocculants are used to precipitate some manure components, they use alone rarely constitutes an adequate or sustainable treatment to minimize the manure problems.

In situations where manure nutrients exceed crop uptake, surplus nutrients must be transported outside the region to prevent an undesirable environmental impact. There are three broad options partly in use in Europe and North America :

- Transport of unmodified manure to other regions,
- Removal of unwanted components;
- Separation and processing of surplus components into a useful product.

Road haulage and, for shorter distances, pipeline transfer, has been used in parts of Europe and North America, especially the Netherlands, as a direct method to re-distribute manure surpluses. To some extent, this redistribution of manure nutrients is a step back towards the former times when farms were smaller and more evenly distributed. However, the environmental impact of the extra transport cost and fuel consumption must be included in any assessment. Pipeline transport is easier once the initial investment has been made but pre-treatment to remove some suspended matter is necessary and the engineering problems increase with distance.

Another option is the removal of manure components such as N through aerobic/anoxic processes, and the organic load, through aerobic and anaerobic treatment. Nitrogen removal is achieved via the process

1 of nitrification (ammonia converted to nitrites and/or nitrates) followed by de-nitrification (nitrites and
2 nitrates broken down to di-nitrogen gas). The technique is used in Brittany, France, to deal with nitrogen
3 surpluses (Béline et al.2004). Any biological process can be expected to breakdown organic matter. With
4 aeration, organic matter is oxidized to produce carbon dioxide and water, while with anaerobic digestion
5 acetic acid is produced and then used by methanogens to produce methane.
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10 Manure components which cannot be eliminated, such as phosphorous and heavy metals, can only be
11 removed by separation, concentration and exportation. This may be the desired process for all excess
12 nutrients including nitrogen and organic matter when there is a recognised value. Separation is achieved
13 through screening, centrifugation and sedimentation. Screening works best with cattle manure where
14 some 30 to 40 % of the solids can be separated from liquids by screens with perforations of 1.5 mm and
15 the resulting solids are ideal for composting. Centrifugation is better adapted to swine and poultry slurries
16 where particles are generally finer than 0.7 mm, because the fine texture of feeds that improves digestion
17 (Barrington, 2002). Again, the final product has a solids content of 30 %, which is ideal for composting.
18
19 The use of flocculants along with centrifugation can further improve the separation of swine and poultry
20 manure solids and nutrients. Sedimentation by gravity using large shallow vessels produces sludge with a
21 dry matter concentration of only 5 to 10 % (Martinez *et al.*, 1995).
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25 Solid products whether from sludges, or solid litter, can be blended or used as they are, to be composted
26 and to produce a useful organic product that is sometimes saleable. The compost process itself adds
27 nothing to the mix but rather produces a stable, aesthetically acceptable and consistent soil amendment
28 which reduces the demand for natural peat, a non renewable resource. Composting reduces the volume of
29 the original material by over 50% (Barrington, 2002) and thus, lowers transportation costs of surplus
30 manure nutrients. Nevertheless, composting is not a free treatment, costing at least 100 Euros or \$150
31 Can. per ton of soil amendment produced, when many soil conditioners are sold on the market for 25
32 Euro or \$40 Can (Barrington, 2002). The addition of some mineral fertilizers to the compost material to
33 balance its nutrient content for specific crops may be an interesting alternative and a method of adding
34 value to cover the composting cost. Further research is needed to evaluate the benefits of adding organic
35 matter to agricultural soils, as the value of organic soil amendments is often based on nutrient content.
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39 Although of limited impact on the natural environment, offensive odours are regularly associated with
40 intensive livestock operations and constitute a nuisance which is no longer accepted by rural residents. In
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1 North America, livestock operators are regularly fined because of odour nuisance. Abatement measures
2 include spreading restrictions associated with wind direction and time of the week or year, use of
3 injection systems and covering manure storage facilities. The only two methods which can reduce manure
4 odours during land spreading are aeration or the oxidation process destroying the organic compounds
5 responsible for odour (Burton et al, 1998), and anaerobic digestion. The use of odour controlling additives
6 remains controversial with limited published work actually demonstrating that they work (Figure 3).
7 Nonetheless, the convenience of applying relatively small quantities of proprietary products to liquid
8 manure makes them popular irrespective of their effectiveness. Along with odour control, aeration can
9 further reduce emissions of methane produced otherwise by anaerobic microbes active at the bottom of
10 the storage (Figure 4). Anaerobic digestion can also reduce offensive odour through the degradation of
11 odorous organic compounds. The methane produced must at least be flared and preferably be used for its
12 energy content.

13 The aeration of manure is an expensive process requiring a considerable amount of energy and this
14 parameter must be considered when assessing the over-all feasibility, benefits and environmental impact
15 of the technology. In North America, livestock producers have limited both of these impacts by aerating
16 manures in the storage tank, for one to two days, just before land spreading. This aeration is done during a
17 rainy day or at night, when offensive odours are not a nuisance (Barrington, 2007a). The anaerobic
18 treatment of manures is a process requiring less energy than aerobic treatment. Although the process is
19 well adapted to tropical regions, a specialist is required to operate conventional anaerobic digesters on
20 livestock operations located in regions with a temperature climate where temperature fluctuations
21 increase the complexity of managing the system. Barrington (2007b) is working on developing an in-
22 storage psychrophilic anaerobic digestion system at no cost besides that of the tank cover, and due to its
23 psychrophilic regime requires no special supervision. This system can also help to reduce ammonia
24 emissions from manure during storage.

25 To conclude on technological options and treatment systems, there is room for a key role in the future for
26 such systems to be more widely implemented, firstly for the control of gaseous emissions (ammonia but
27 also greenhouse gases) and secondly for the control of environmental sanitation.

28 In regard to controlling or reducing greenhouse gases, there is not at the present a consensus but rather
29 “contradictory” results. For instance Melse and Verdoes (2005) through an evaluation of four Farm-scale

1 treatment systems found that the highest level of greenhouse gases emissions was observed with the
2 nitrification/denitrification system (up to 48 kg [carbon dioxide equivalents] t⁻¹ [manure] compared to 12-
3 17 kg [carbon dioxide equivalent] t⁻¹ manure for the other three systems (Figure 5). But mostly the GhGs
4 losses occurred through nitrous oxide emissions, which indicates a lack of control of the system by the
5 manufacturer. In particular, the use of continuous aeration (versus intermittent) induces considerably
6 large nitrous oxide losses (Béline et al., 1999). On the opposite, a long-term and repeated campaign of
7 measurements (and based on comparing various farm treatment plants) conducted by Loyon et al. (2007)
8 demonstrated that the conventional management of the raw slurry compare to three other treatment
9 options emitted more GhG as well as ammonia (Table 7).
10 This illustrates once again the need to clarify the objective of the treatment systems before evaluating its
11 “performances” per se, but also the need to implement reliable systems based on “sound” science.
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25 ***4.2. Adaptation of natural environments: soil filter systems, constructed wetlands***

26 Land treatment is based on the physical, chemical and microbiological interactions between the
27 components and the micro-organism of both the soil and the waste. As manure moves through the soil
28 profile, a high degree of purification can occur so long as the degradation and plant uptake capacity is not
29 exceeded (Hawkins et al. 1995). Such a soil filter was introduced by Szögi et al. (1997) to treat the
30 effluent of an anaerobic lagoon treating swine manure. The media, consisted of marl gravel, could
31 remove 54% of chemical oxygen demand (COD) and 50% of total suspended solids (TSS). Removal
32 efficiencies for total phosphorus (TP) ranged from 37% to 52% while for total nitrogen (TN), up to 24%
33 was converted to nitrite and nitrate-N, which was denitrified through constructed wetlands. Such higher
34 TP removal efficiencies were likely to require a filter medium change once saturation was reached.
35 Boiran et al. (1996) removed nitrogen from pig slurry using a forced nitrification step within gravel
36 columns. Nitrogen removal of 4% to 38% and ammonium-N oxidation into nitrite and nitrate of 64 to
37 98% was achieved, depending on the gravel used in the column, whether calcareous or siliceous in
38 nature. A four-stage soil filtering system was investigated by Kuli et al. (1996) in Hungary for the
39 treatment of highly diluted pig slurries with 0.4 to 0.6 % TS. The simple low-cost system is operated
40 from a straw pre-filter followed by a beds of wood shavings, gravel and sandy soil. The system was able
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1 to take loads of 2.5-5.0 m³/day and its overall COD and BOD removal efficiencies were 43-76 and 46-88
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3 % respectively, while 58-99 % of the TSS were removed.

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5 A soil treatment process called a barriered landscape wastewater renovation system (BLWRS) was
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7 developed in the USA and consists of a mound of soil over an impermeable barrier and a drainage
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9 system. Thus, an aerobic zone was created in the top portion while an anaerobic zone was created in the
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11 bottom portion of the BLWRS (Ritter and Eastburn, 1978). Evaluated for two years for the treatment of
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13 liquid dairy wastes, the system was capable of removing 90, 90 and 99 % of the COD, N and P,
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15 respectively. Again, the filter medium likely required replacing once saturated with P.

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17 In France, the soil filter system, Solepur, was highly successful at removing organic matter and nitrogen
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19 (N) from pig slurry during its first five years of operation (Martinez, 1997). The system consisted of
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21 three operations: application of large volumes of pig slurry to a managed field; collection and treatment
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23 of the nitrate-rich leachate; and irrigation of the treated water over other fields. This study measured the
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25 environmental implications of applying excessive volumes of slurry to cropped land and also improved
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27 knowledge pertaining to N cycle within the soil profile.

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31 As regards the treatment of livestock effluents and manures, whatever the options considered either being
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33 so-called “technological options” (based on energy, concrete, steel, chemicals e.g. fossil fuel intensive) or
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35 “natural options” (based on sun, wind, land, seeds e.g. land intensive) there is clearly no better solution,
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37 but rather a range of options which needs to be adapted and implemented according to the local situation
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39 and context (social, economical, regulatory).

40 41 42 43 44 45 **5. Conclusions**

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49 Looking towards the future, we could try to imagine what livestock production and waste management
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51 should be and what it may become :

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56 1. Livestock production should have a better integration within other agricultural and agri-food activities
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58 to have a better use of both its inputs and its outputs. For its inputs, the necessary increase in animal

1 production required in the future will not be reach by genetic improvement of animals nor strong increase
2 of the "average daily gain". Moreover, the human and economical pressure on cereals will compete more
3 and more with livestock production. We can expect that in the future, the cereals used for animal feeding
4 will be slowly replaced by co- or by-products from agri-food activities, allowing a reduction of the cost of
5 animal feeding and the development of recycling systems of so far unused products.
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13 2. For the outputs, it is also clear that there is a need to imagine new waste management methods that
14 would protect the environment and allow manure management to switch back to a recycling view of
15 manure handling. Within these new techniques, the early separation of liquids from solids in livestock
16 houses may be of particular interest since it reduces gaseous emissions in the buildings and it generates
17 liquid and solids that can be processed separately.
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25 3. Techniques allowing nutrient recycling from wastes, especially phosphorus, should also be developed
26 as well as any techniques allowing an economical and environmental friendly benefit like a better
27 agronomical use of manure or biogas production from manure.
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33 4. The ideal situation would be to work at the same time on both the inputs and the outputs of livestock
34 production and on its integration in its "regional" or geographical aspects. However, to reach such a goal,
35 we need to consider all treatment aspects not only the constraints whatever they are (environmental,
36 sanitary etc) but also the overall consequences integrating economical parameters like cost of livestock
37 buildings, evolution and depletion of fuel energy, phosphorus and may be cheap cereals.
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45 5. We also need to integrate possible stronger policies on environmental protection such as the necessity
46 to include new "emerging" pollutant like antibiotics, endocrine disrupters, antibio-resistant pathogens, etc.
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51 6. The development of such new systems will require the development of new measuring devices and
52 global methods to assess the viability of production chain and food supply. These systems are currently in
53 progress through the Lyfe Cycle Assesment methods.
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Table 1. Projected trends in production of various livestock products, 1993-2020.

Region/product	Projected annual growth of total production		Total production	
	1993-2020		1993	2020
	(%)		(million metric tons)	
Developed world				
Beef	0.6		35	38
Pork	0.4		37	41
Poultry	1.2		27	36
Meat	0.7		100	121
Milk	0.4		348	371
Developing world				
Beef	2.6		22	44
Pork	2.7		39	81
Poultry	3.0		21	47
Meat	2.7		88	183
Milk	3.2		164	401

From Delgado et al. (1999)

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Table 2. Global nitrogen intake for nutrition of humans and animals.

Category	Consumption of N (million tons)
Humans (inhabitants 5.6 billions)	23.7
- via vegetable products	15.2
- via animal products	8.5
Pigs and poultry	21.6
Cattle, sheep, etc.	92.8
- via feedstuffs	9.8
- via grassland products	83.0

From Bouwman & Booiij, 1998

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Table 3. Indicative values for the N transfer efficiency at the farm and underlying levels.

Step(s) in the N cycle	Transfer efficiency (%)
From feed to milk and meat	20-40
From manure to soil	50-90
From soil to crop	40-80
From crop to feed	80-90
Whole dairy farm	10-40
Whole arable farm	40-80

From Schröder (2005)

Table 4. Annual global methane and nitrous oxide emissions.

	Methane (Million tons)	Nitrous oxide (Million tons)
Waste handling	56	0.27
Biomass burning	7	0.39
Agriculture	134	9.65
Industrial processes	1	0.74
Biofuel	14	0.18
Fossil Fuel	91	0.29
Total	302	11.52

From EDGAR (2006)

1
2 Table 5. Greenhouse-gas emissions per year from livestock

	Carbon dioxide (global, 2002)	Methane enteric (global, 2004)	Methane manure (global, 2004)
Cattle	1906	75*†	8‡
Small ruminants (sheep and goats)	514	9	0.3
Pigs	590	1	8
Camels	18	-	-
Horses	71	-	-
Poultry	61	-	-
Total	3161	86	18

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13 Data are million tonnes of gas. * Dairy cattle account for a quarter of enteric methane emissions from
14 cattle. † Buffaloes contribute 9 million tons. ‡ Buffaloes contribute 0.3 million tons.
15 From McMichael *et al.*, (2007)
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Table 6. Airborne dust, bacteria, fungi and endotoxin concentration in livestock buildings.

	Cattle buildings	Pig buildings	Poultry buildings
Inhalable dust (mg/m ³)	0.4	2.2	3.6
Reparable dust (mg/m ³)	0.1	0.2	0.4
Inhalable endotoxin (EU/m ³)	140.0	670.0	2000.0
Respirable endotoxin (EU/m ³)	10.0	70.0	210.0
Bacteria (log cfu/m ³)	4.3	5.1	6.4
Fungi (log cfu/m ³)	3.8	3.7	4.0

From Takai and Petersen (2002)

Table 7. Estimation of annual emissions of specific gases for a conventional system and for 3 options of biological treatment.

	NH ₃ (kg N)	N ₂ O (kg N)	CH ₄ (tons C)	CO ₂ (tons C)	CH ₄ +N ₂ O (tonsCO ₂ eq.)
Traditional system	824	0	14.7	11.5	413
Treatment option 1	265	139	4.2	7.6	185
Treatment option 2	392	133	4.3	12.6	186
Treatment option 3	577	121	4.7	16.3	190

Treatment option 1 : storage + biological treatment + decanting

Treatment option 2 : storage + compacting screw + biological treatment + decanting

Treatment option 3 : storage + decanter centrifuge + biological treatment + decanting

From Loyon et al. (2007)

Table 8. Concentrations of bacteria (per gram of wet weight) and occurrence of *L. monocytogenes* in raw manures and treatment by-products from 17 piggeries

Manure treatment	Type of product (number of samples)	<i>E. coli</i>	<i>Enterococci</i>	<i>C. perfringens</i>	<i>Salmonella</i>	<i>L. monocytogenes</i> ^a
		Mean (min- max)				
One month anaerobic storage	Raw manure (12)	2 10⁴ (0.02-5. 10 ⁴)	7 10⁴ (0.2 to 31 10 ⁴)	9 10³ (0.08 to 72 10 ³)	0.1 (ND to 0.9)	50%
4 to 6 months anaerobic storage	Raw manure (5)	5 10⁴ (0.2 to 10. 10 ⁴)	4 10⁴ (0.1 to 14 10 ⁴)	1 10³ (0.5 to 4 10 ³)	2 (ND to 11)	0%^e
Raw manure physical separation	3 months stored raw manure separated solid (4)	12 (ND to 38)	ND ($< 10^{-3}$)	6 (ND to 19)	ND ($< 4 10^{-4}$)	0%^e
Aerobic digestion followed by anaerobic storage	Sludge from treated manure (10)	5 10² (0.4 to 10. 10 ²)	4 10³ (0.1 to 6 10 ³)	8 10³ (0.1 to 52 10 ³)	6 10⁻³ (ND to 0.04)	20%
Aerobic digestion followed by sludge separation and pond	6 months stored liquid from treated manure (8)	4 (1 to 14)	77 (ND to 453)	40 (ND to 210)	ND ($< 4 10^{-4}$)	0%^e

^a frequency of detection of *Listeria monocytogenes* (%); ND, not detected.
From Pourcher et al (2007)

1
2 Legends of figures
3

4 Figure 1. Estimates of cattle and pig numbers by continents in 2004 (from Windhorst, 2006, Source FAO
5 – Database)
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7 Figure 2. Main pathways of sources and sinks of greenhouse gases associated with agriculture (from
8 OECD, 2001)
9

10 Fig. 3: Cumulative methane emissions during storage for an experiment comparing a control raw
11 slurry(●) and the effect of addition of three commercial additives: NX23 (▽) Stalosan (■), Biosuper
12 (◇); standard deviation is plotted for each measuring point (from Martinez *et al.*, 2003)
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14
15 Fig. 4 Cumulative methane emissions during storage for an experiment comparing a control raw slurry
16 (●), a separated slurry (▽) and a slurry previously aerated (■) (fine bubbles system); standard deviation
17 is plotted for each measuring point (from Martinez *et al.* 2003)
18

19 Figure 5. Average emission of NH₃, CH₄, N₂O, greenhouse gases (GHG; sum of CH₄ and N₂O), and
20 odour from four treatment systems for liquid pig manure; emissions are expressed per tonne of manure
21 input; for system 4, only odour and NH₃ emissions were measured: □, system 1, straw filtration; ■,
22 system 2, mechanical separation; ▨, system 3, nitrification/denitrification; ▩, system 4, evaporation
23 (from Melse & Verdoes, 2005)
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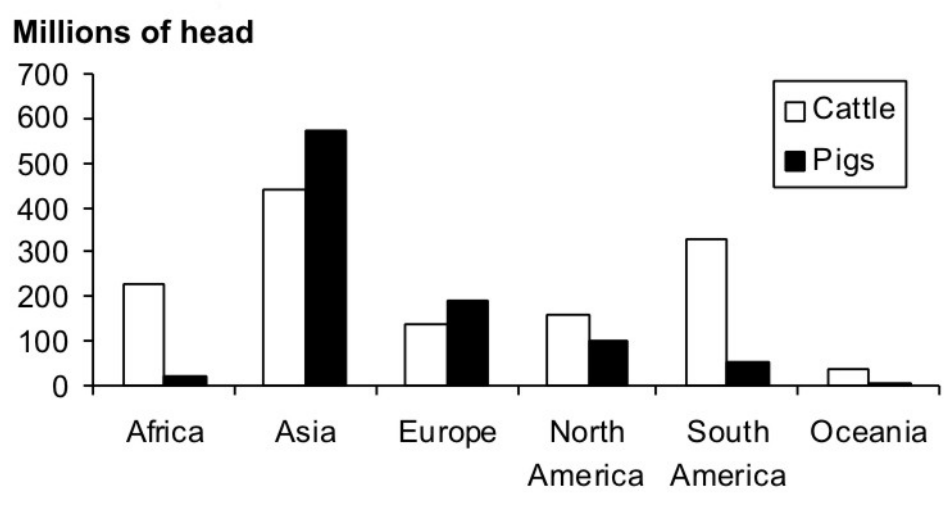


Figure 1

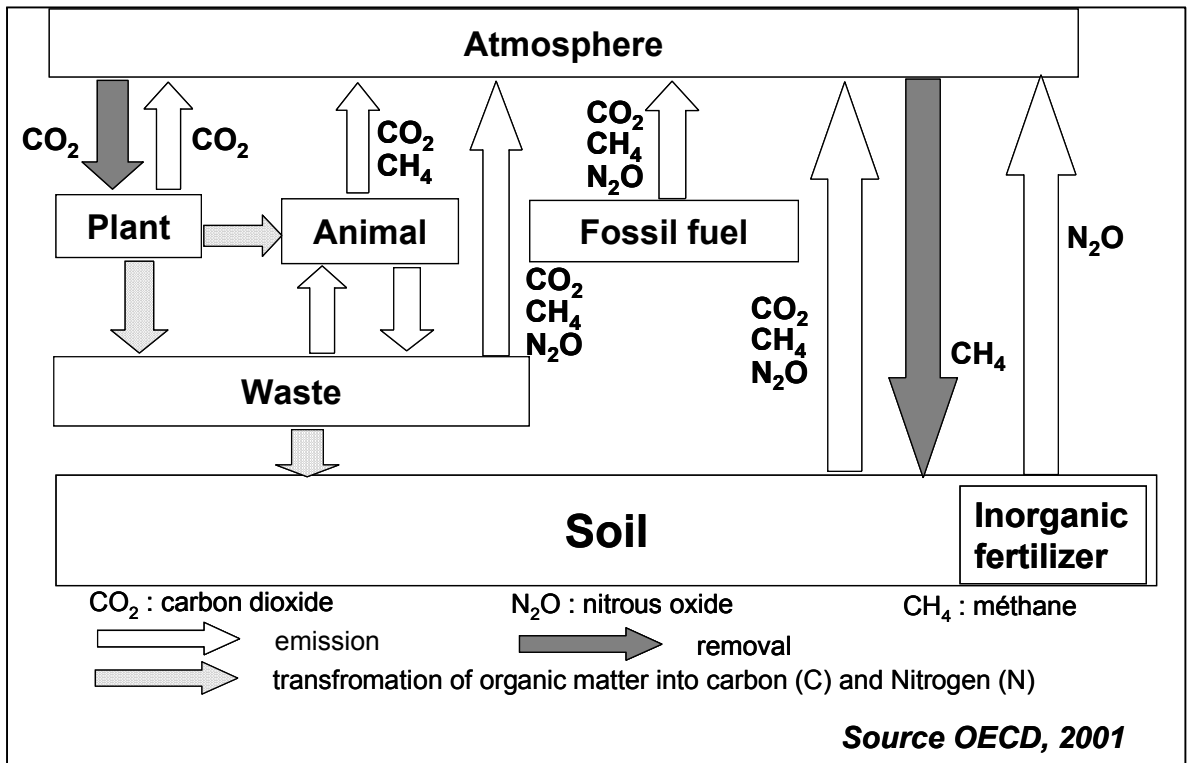


Figure 2

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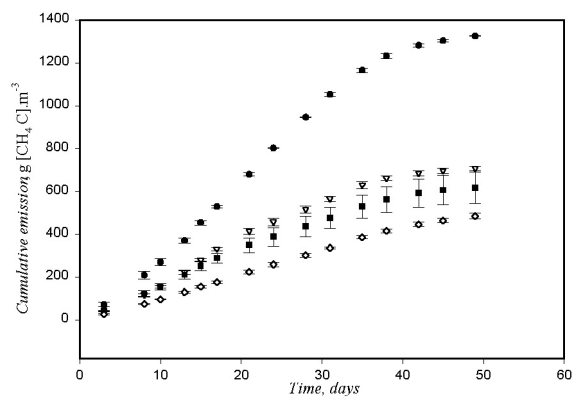


Figure 3

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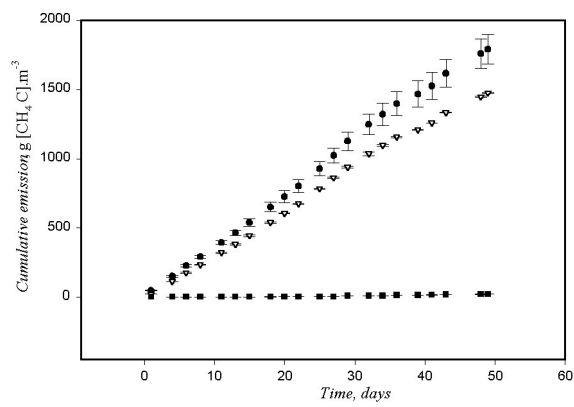


Figure 4

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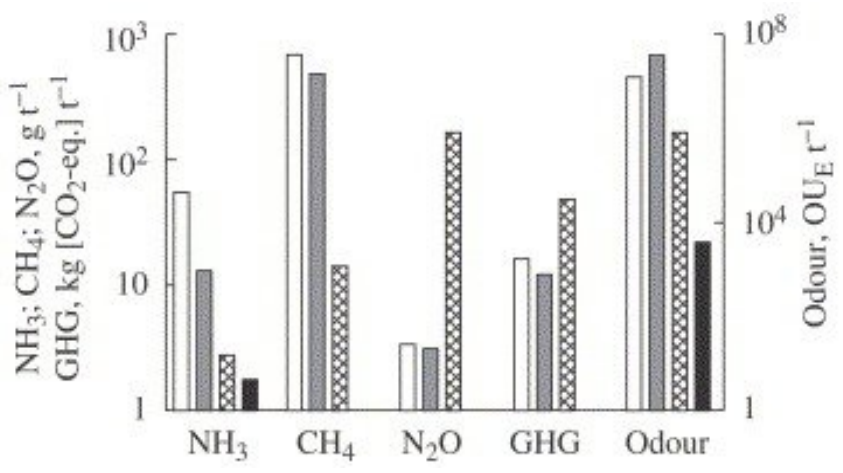


Figure 5