Rethinking wastewater biosolids, phosphorus recovery and sustainability

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Abstract: This paper aims at bringing about an urgently required, scientific shift of perception in the field of biosolids management and phosphorus recovery from domestic wastewater. The paper shows that under a combination of the prevailing sludge, phosphorus and sustainability paradigms, the worldwide rapidly growing issue on biosolids production leads to a paradox that proper management cannot resolve alone. Change demands for a sound fundamental ecological approach in all sectors involved. To produce low quantities of biosolids of high fertilizing quality that can harmlessly be stored or, functionally applied in relation to agricultural demand is a master challenge for the future, not only technologically. A deep transformation of societal beliefs and structures, economic processes and environmental understanding is equally imperative. The traditional pillars of sustainability will collapse under the tons of daily sludge production unless individually fortified and collectively integrated in a fundamental ecological, single-bottom-line concept of sustainability. Moving forward by meticulously matching, in all domains, practice with ecological theory and science will develop the synergy required for progress and success. The best management device reverses to “act globally, think locally”.

Keywords: Biosolids; bottom line; ecology fundamentals; paradigm; phosphorus; sustainability.

INTRODUCTION

Environmental laws and policy, economic mechanisms, public opinion and the technological state-of-the-art are the major drivers that govern daily sludge management practice. Within the general tension field between social activism, economical forces and political governance, objectives are set under the widely accepted umbrella of health risks minimization and sustainability development (Dentel, 2007). Design and implementation of feasible practical solutions to meet these objectives is a subsequent task for science and technique. Due to its subordinate position, the strategic potential of science to guide societal goals in this respect remains largely unused (Lettinga, 2006). There is a real danger of undesired developments that act against true long-term sustainability to so be promoted, science being essentially powerless in the process (Leblanc et al, 2007). This trend needs to be reversed. For satisfactory biosolids management purposes, a science of sustainability and the environment should provide the vision, set the course and gain through its holistic outlook, its objective rationalism and its practical applicability the synergy of all societal drivers involved.

Why does science lag behind in sustainability issues? Behind the banner of global sustainable development, the International Water Association (IWA) established the concept of ecological sustainability in the water sector at the heart of its activities. Within the IWA’s Sustainability Programme (2005), there has been an intensive discussion on the need to adopt a more rigorous definition of sustainability. It was however felt that shaping sustainability practice principles in case-by-case approaches is the best way forward for the more immediate future. The expectation that practice will inform and shape theory in the longer-term will however remain wishful thinking without true attempts in this direction. In scientific research and development, theory and practice must go hand in hand. Any practical case study basically offers an opportunity to start shaping theory. Even the best sustainability practice needs a proper scientific backbone to survive.

The management of biosolids and phosphates originating from domestic wastewater treatment systems is a topical case, in which the debate on sustainable options may not only lead to more attractive and safer
practical solutions, but may simultaneously move forward our scientific perception of the sustainability concept itself. This paper takes up the challenge of dynamically integrating practical, scientific and theoretical aspects of the issue.

SCIENTIFIC-TECHNICAL BACKGROUND

Reducing the domestic sludge issue

Sludge properties and characteristics essentially are a function of the composition of the wastewater to be treated and the treatment process applied. Given the general composition of sewage sludge (Rulkens, 2004), domestic wastewater can roughly be divided in two fractions as far as treatment and recovery of materials are concerned: the valuable organics and inorganics, and the toxic organics and inorganics. The majority of hazardous compounds in wastewater are source reduction sensitive. From a rigorous sustainability point of view, this fraction should be banned in biological treatment systems by means of effective public information, legislative and technical measures. Preventing biosolids pollution this way would help relativize the risk/safety-based sludge management paradigm, and alleviate the inflated concern for health and hygiene (Kroiss, 2004).

The remaining valuable fraction, approx. 60% of the sludge DS, originates from organic carbon, nitrogen, phosphorus compounds and other harmless inorganic minerals and elements present in sewage water. For the purpose of this paper the domestic sludge issue is reduced to this fraction only, which falls technologically under an ecological sustainability paradigm as clarified below.

Ecologically sustainable sludge valorisation

Wastewater treatment. The essential purpose of biological wastewater treatment (WWT) is to improve the C:N:P stoichiometry in the effluent to allow for a harmless discharge to receiving waters. The essential function of the microbiology involved is to transform the instable organic compounds in sewage to corresponding more stable inorganic forms, thereby recycling important life-sustaining elements (CHONP) to their natural liquid, gaseous or solid reservoirs where a new cycle of usage starts. The microbially mediated processes involve the transformation of energy and matter present in the influent. They proceed according to natural thermodynamical and ecological principles. The sustainability criterion is dictated by the imperative of all waste components to be transformed, removed, recycled, recovered with a minimum overall input of exogenous energy and materials (Lettinga, 2005). Best practice biological WWT is a self-sufficient process. Sustainable technology (Figure 1) is the intelligent, careful application of the fundamental principles of ecology (Odum and Barrett, 2005).

Figure 1 The criterion for sustainable technology (ST) in biological WWT is an ecological one, integrating energy, carbon and nutrient cycles.

Sludge generation. The valuable wastewater fraction is processed in anaerobic, aerobic or combined anaerobic/aerobic treatment schemes, each yielding sludge with typical quantitative and qualitative characteristics. As a general rule, strategies that minimize the conversion of organic matter into sludge biomass and reduce the volatile fraction of the solids will enhance sludge properties. Control and optimization in the WWT line of solids quantity, settleability, stabilization, mineralization and water content, significantly simplifies subsequent sludge treatment schemes.
Based on the preceding rationale and the range of available microbiological processes, Davelaar (2007) concludes that domestic wastewater typically requires integrated anaerobic/aerobic biological nutrient removal (BNR) technology to produce concurrently, good quality effluents and low quantities of highly recyclable biosolids (Fig 2). The bio-P process for WWT and the challenge of its optimization are attributed a key role in this achievement.

**Figure 2** Rethinking the treatment of domestic wastewater according to the fundamental ecological recycling principles.

*Biosolids valorisation.* Biological WWT combines liquid, solid and gaseous aspects, but sludge addresses exclusively the solid state, thereby again surprisingly simplifying the issue (Fig 2). As has also been indicated by Kroiss (2004), the solid fraction comprises essentially two valuable parts: organic matter and phosphates. Thoroughly mineralized organic C can safely and sustainably be disposed and reused in land and soil application. Phosphates are to be extracted and recovered for reuse in P-industry and fertilizer industry, or remain fixed in the biosolids for direct agricultural use. The technological frame for domestic sludge valorisation being set, what are the prospects for the other drivers of the issue to adopt and support ecologically sustainable biosolids management?

**SUSTAINABILITY: A MULTI-SECTORAL APPROACH**

**The ideology and its opportunity**

The four main drivers of biosolids management are linked by a common, strong concern for sustainable development (see Figure 3). Until now the concept of sustainability basically remains an ideology resting on an extreme degree of consensus, to which its success is undoubtedly due. Understood in a negative sense it may seem to only justify and serve the perpetuation of existing structures and policies (Lettinga, 2006). But: “Frameworks must be lived with and explored before they can be broken” (Kuhn, 1996). It is through rigidity, resilience and resistance to new and competing conceptual worlds that an established, aging paradigm methodically prepares the way for its own change. Conversely, it may be expected that the criterion of ecological sustainability once better scientifically defined, has the propensity to trigger a profound movement of change. Change begins with the fundamental question to question the question in question: what is ecologically sustainable biosolids management? Phosphates management? How can it be assessed?

**Figure 3** A common concern for sustainability has the propensity to integrate divergent sectors.
The triple bottom line model (TBLM) and its dualistic perception

A bottom line originally is an economy criterion, referring to a decisive profit/loss turning point. The TBLM is a common and valuable instrument in sustainability issues. It integrates the three classic pillars of sustainability: economical viability, social responsibility and environmental protection. The model is widely used to assess sustainability, primarily of economic activities by evaluating their respective influences on both other domains. In its broadest sense, TBL modelling embraces the set of interests, issues and processes that human activity should address in order to create economic, social and environmental value whilst at the same time minimizing undesirable consequences in these domains. Curiously, neither technology nor science or ecology is made explicit in the TBLM, although they are implicitly involved.

Figure 4 The two extreme perception models of the Triple Bottom Line.
(Ec = economical So = social En = environmental)

Two opposite versions of the TBLM coexist (Figure 4), the anthropocentric and the ecocentric view of sustainability, the first having a broader use in practical assessments. The difference in view has a cultural root (Van Peursen, 1974). It results from man's inherent perception of nature and inclination for self-positioning within the natural dimension: assertive and controlling versus integrative and being controlled. This perception is known to change and evolve with time.

BIOSOLIDS AND P-REUSE: A PARADOXICAL CASE IN SUSTAINABILITY

In this section a brief, qualitative sustainability assessment of the previously discussed biosolids and phosphates management issue is made using the anthropocentric variant of the TBLM.

Sustainable management assessment with TBLM

The case of phosphorus. From an environmental point of view, the most critical but valuable component in sludge is phosphorus (P). The urgency to recover and recycle this important life-sustaining element follows from the limitation of global reserves (economic interest), and the increased trend to break the natural P-cycle (environmental interest). However sustainable P-recovery technology is still in a stage of early development and economically uncertain (Balmér, 2004), but prospectives are encouraging as outlined above. Paradoxically, neither economical incentives nor social pressure currently drives legislation, technology and marketing developments to accredit the true ecological value of phosphates. There is lack of synergy from the economic and social drivers, largely due to a lack of general public awareness of the issue (Figure 5).

The case of biosolids. Agricultural use of biosolids/sludge remains worldwide the best economic and a widely accepted environmental solution (see Figure 5), at least there where hazardous substances play no role of importance or can be controlled through source reduction. Paradoxically, sludge application in agriculture has become increasingly unpopular from a social point of view, mainly due to over-emphasized concern with associated health risks. Today's poor acceptance of wastewater sludge as valuable agricultural product strongly contrasts with traditional soil and waste management views and practices. This is the more surprising since customs of primitive cultures are recognized to be a source of knowledge, purposely sought for in modern sustainability practice.
TBL modelling for sustainability assessment of P-recovery and reuse from sludge, and biosolids recycling to agriculture/land.

**TBL Model and the Domestic Sludge Management Paradox**

The ecocentric TBLM ends up in the same paradox as its anthropocentric counterpart. Environmental and economical interests do not match satisfactorily, and the societal dimension seems completely out-of-focus in the entire issue on sustainable management of biosolids and phosphates. The negative public perception of wastewater and sludge could grow so powerful as to prevent a traditionally successful and sustainable, agricultural management pathway from being technologically reinvented and beneficially implemented. Moreover, our collective societal perception of sustainability proves severely distorted. In brief, the sustainability paradigm falls short as the inaptness of its TBL tool indicates. The value of the model itself is now questioned: does it urgently need revision?

**THE TBL MODEL FOR SUSTAINABILITY: THEORETICAL IMPLICATIONS**

**Beyond Paradoxical Thinking**

The occurrence of a paradox is in itself an indication that a change in view is necessary. The considered issue being unsolvable within the existing thinking framework, this framework needs to be enlarged with a new dimension. New perspectives generate new solutions. Theoretical contradictions are like impossible puzzles and the perceptual ambiguity of paradoxes is very similar to that of optical illusions. Their solving requires an exercise in out-of-the-box thinking or, just another state of mind. Figure 6 illustrates the point with a typical brain teaser.

**Figure 5**

<table>
<thead>
<tr>
<th>Case</th>
<th>+ environmentally pressing</th>
<th>± environmentally complex</th>
</tr>
</thead>
<tbody>
<tr>
<td>phosphates</td>
<td>± economically equivocal</td>
<td>+ economically attractive</td>
</tr>
<tr>
<td>recycling</td>
<td>0 socially blank</td>
<td>- socially repulsive</td>
</tr>
</tbody>
</table>

**Figure 6**

The shift to a new more inclusive dimension is a paradigm shift, illustrated here by the impossibility to connect, free of encroachments, the nine dots with four lines without making an out-of-the-box movement.

By simply replacing the nine dots with the nine essential points summarizing the sludge issue, namely: sustainability, economical value, agricultural/soil resource, controlled use, safety, minimized quantity, mineralized quality, P-recovery, P-reuse and the lines with the four main drivers involved, namely environmental, economical, social and technical-scientific, the paradox and its resolution pathway become evident. Connection or integration of all interests demands for a new dimension. What is the nature of this fourth, integrative dimension?
Expansion to a Quadruple Bottom Line Model?

Rethinking the anthropocentric-ecocentric polarity. If a sustainability paradigm is to converge interests as to achieve a common objective (Figure 2), so should its tools. The dual view of sustainability reflected in the TBL twin models is a theoretical anomaly of the prevailing paradigm in the sense of Kuhn (1996). It essentially divides and creates tension. This tension originates, as mentioned above, from natural human subject-object perception differences. Being a characteristic intrinsic to the process of culture itself (van Peursen, 1974) it is also recognizable in the practice of science (e.g. Cartesian paradigm versus the new holistic sciences). The subject-object dualism is very present too in the broad environmental discussion; it is the famous man-nature dilemma. But, as quantum physics and eastern mysticism independently show (Capra, 1983), polarization offers a unique opportunity for integration and perception shift to a new, more inclusive dimension.

Beyond TBLM polarity: the fundamental ecological dimension. Ecology is a scientific discipline that transcends the organism-environment polarity *per se*. Ecology studies the functional relationships between living systems and their immediate surroundings; it is an integrative science. Organism and environment are perceived as opposed but interdependent and complementary, instead of mutually exclusive and incompatible. Merely the focus changes, from one-or-the-other to both-at-the-same-time. Fundamental ecology being the study of the global household, it is the best candidate of sciences to rationalize sustainability. Managing the global household is the subject of economics, for this purpose ecology’s functional counterpart discipline (Odum and Barrett, 2005).

![Figure 7](image)

**Figure 7** Fundamental ecology overarches man-nature dualism, creating dynamic unity.

Human ecology is generally understood as a subdiscipline of the social sciences. As a living being, man is however not exempted from adapting to the natural laws ruling the biosphere, undoubtedly the ultimate bottom line guiding all human activities on earth. Within a fundamental ecological dimension, it seems possible to reconcile the anthropocentric TBLM with its ecocentric variant (Figure 7), resulting in only one bottom line, the ecological, including the three others (Figure 8).

A *global ecological BLM and ecological governance*. Figure 8 illustrates that in such ecological sustainability model, the whole is more than the sum of its parts. The emerging property is true ecological governance. The originally economical, single-bottom-line concern has made a full circle, to finally reappear on a higher level of global organization as an ecological sustainability concept.

In recent years many attempts to expand the TBL to a QBL model have been undertaken. Interestingly, the nature of the advocated new dimension relates to the identity of the driver concerned. Economists opt for financial, environmentalists for technological or educational QBLMs. The social-public sector puts great emphasis on the introduction of cultural, spiritual, ethical dimensions. Another very important aspect emerges from the political-managerial arena on different levels of organization, namely that of governance. Governance is the faculty to govern, which is to control and integrate divergent interests based on a governance paradigm.
The fourth (or first) dimension of ecological sustainability is its governance context, ecology fundamentals, rather than governance itself. Governance in this perspective it is the strategic position in the middle.

![Diagram](image)

**Figure 8** Synergy of environmental, social and economic drivers within a global ecological BLM with ecological governance (EG).

**PRACTICAL SIGNIFICANCE**
Returning to the paradox currently impeding sustainable management of biosolids and phosphates as seen through the reality of the TBLM (Figure 5), how would an ecological BLM as rationalised above (Figure 8) help tuning in all the drivers involved?

**Gaining synergy for ecologically sustainable biosolids use and disposal**
Independently of another, the subdomains need to reposition and rearrange themselves within the new ecological dimension and to reshape mutual functional relations. Because the necessity to change affects all and the nature of the problems faced is essentially similar, because interconnectivity is already well developed, the process will be facilitated. The governing, global ecological principles furthermore offer local, strategic and executive management the objectives and the scientific fundament to help restructure and align economic, legislative, public domains. Ecological education of all stakeholders, managers in particular, with respect to the fundamental ecological meaning of sustainability and the ecological dimension of sludge and wastewater treatment is, without any doubt, one of the first challenges to take up. In case-by-case approaches, practice whether from economical, social or environmental background, must be accompanied by ecological science and theory to pilot the process of change.

**Ecological sludge valorisation calls for a technical-scientific paradigm shift**
Technology faces the major challenge to effectively realise the production of economically viable, ecologically sustainable biosolids from domestic wastewater. Davelaar (2007) concludes that the state-of-the-art must undergo a radical paradigm shift, from advanced sludge treatment to sludge generation technology directly coupled to biological WWT. In this new approach, the objective of domestic sludge valorisation will directly counterchallenge current BNR technology to undertake an optimization effort, aiming at advanced mineralization of activated sludge and sustainable recovery of biologically fixed phosphates. In this context the bio-P mode of WWT has a particular significance. However, its full exploration and exploitation also requires a paradigm shift, namely in activated sludge microbiology (Davelaar, 2001). This is due to the occurrence of a fundamental theory gap with respect to the microbial part of the phosphorus cycle on earth, for which Davelaar (1993) has proposed an integrated ecological theory. To realise these goals in fundamental science and their application, support and synergy from the economic and social drivers are badly required. To act globally, think locally and think globally when acting locally both-at-the-same-time.

**SUMMARY AND CONCLUSION**
The reported study is a case approach conceived to simultaneously move forward the issue on biosolids and phosphates management from domestic wastewater, and the global sustainability agenda. The three issues are interconnected in practice. In the three issues, there is a growing tension between new scientific views and theories and the evolution of the general public opinion. Environmentally sound outlet prospectives for valorised biosolids and recovered phosphates are currently poorly supported by the economical and social-public sectors.
The root of the problem was analysed to be a shortfall of our current sustainability paradigm, due to a rudimentary scientific definition of its leading principle. TBL modelling of the case resulted in an irresolvable, paradoxical mismatch between the interests of the drivers involved. The paradox proved intrinsic to the TBL model itself, opening the doorway for the introduction of a new dimension. The ultimate profit/loss turning point in sustainability is governed by fundamental ecological principles, themselves resting on the laws of thermodynamics. Therefore an ecological, single-bottom-line model better models sustainability. Fundamental ecology, the integrative systems science of the biosphere, is the best candidate of sciences to start rationalizing sustainability. Shifting to an ecological sustainability paradigm, thereby assessing human activity against this only realistic background is expected to generate a powerful domino effect, triggering change ubiquitously. “Perception becomes Reality” so goes the saying: if we succeed to reverse our perceptions, we will succeed to change our reality.

REFERENCES


