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Sludge Management: Integrating the Principle of Circular Economy into the Concept of Sustainability

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Abstract: The development of sustainable sludge management systems requires looking at them with a new vision in which the concepts of SD (Sustainable Development) must integrate those of CE (Circular Economy), both concepts subject to the principles of TD (Thermodynamics), thus allowing the adoption of actions that are all the more effective the more complete the evaluation of the social dimension has been. This involves a new "Way of thinking" which sees the sludge system as the "Locomotive" of the entire wastewater/sludge treatment train and is developed through "Ways of acting" which includes both "Technical" actions to maximize recoveries of useful materials and/or or energy, and "Socio/Institutional" actions to overcome barriers linked to local cultures and traditions, also considering that the specific local context heavily influences the choices capable of satisfying the concepts of CE. It follows the need of issuing realistic and applicable regulations and overcoming social barriers, such as lack of infrastructure and/or qualified personnel, to achieve an effective integration of the concepts of CE with the more general ones of sustainability.

Key words: Circular economy, regulation, sludge management, standardization, sustainability.

1. Introduction

Tasks 6.2 and 6.3 of the Sustainable Development Goals of the UN Agenda 2030 are addressed to "achieve access to adequate and equitable sanitation and hygiene for all..., ... substantially increasing recycling and safe reuse globally..."

This will certainly involve (i) a greater production of wastewaters resulting from the growing availability of household running water, (ii) extended sewerage, (iii) new treatment plants and (iv) upgrading of existing facilities to comply with more stringent environmental quality requirements imposed by legislation, thus leading to an overall increase in sludge/biosolids production. This development is counterbalanced by the innovation of new processes, that are less sludge-producing.

Managing this development in a sustainable way represents one of the most critical issues that modern society must face [1].

CE (Circular Economy) has gained popularity, and it can certainly contribute to the sustainable use of resources. CE and SD (Sustainable Development) are often considered either to be overlapping concepts or alternative concepts. However, the CE concept in its theorization includes the concept of SD, giving great importance to the reduction of the consumption of virgin materials, through the design of products with a longer life cycle and with greater possibility of reuse/recycling, while the social dimension of sustainability is only marginally addressed.

This means that not all the requirements of the SD concept can be fully and effectively satisfied by the application of CE. Furthermore, it must be considered that SD and CE concepts must meet the principles of TD (Thermodynamics).

This article discusses the extent of the impact that the practical application of CE principles can have on the development of effective strategies for sustainable sludge/biosolids management.

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For a more immediate understanding, the correlation and interdependence between SD, CE and TD have been graphically represented by the three fundamental geometric figures, namely triangle, square and circle.

2. Background

2.1 The SD Concept

Given that a "concept" consists of an ideal thought that is formed by putting together various principles that the mind wants to have present, sustainable sludge management means that the consumption of renewable resources does not exceed nature's ability for replenishment, i.e. the natural/virgin resources are not used up faster than they can be naturally replenished.

For this to happen, a "sustainable" system must simultaneously be "environmentally bearable", "economically convenient", and "socially acceptable".

It is also important to say that the SD concept must be seen from a "relative, not absolute" point of view, because it depends on the local context, which is defined by geographical, climatic, economic, technological, infrastructural, social, etc. conditions, and on the boundaries of the system, which must include the processes and operations composing the system completely. The greater the extension defined by the boundaries, the greater the sustainability of the system "as a whole", i.e. a single equipment/action cannot be defined as sustainable by itself without considering upstream and downstream equipment/actions of the operational cycle [2].

The main challenge for evaluating sustainability is that a clear and unique conceptual meaning is not supported by commonly accepted quantification procedures [3].

Considering that in a triangle each side is connected to all the other sides, it follows that the concept of SD can be well represented by this geometric figure in which the environmental, economic and social aspects are closely connected to each other. As shown in Fig. 1, when a system is well-balanced in terms of sustainability, the triangle assumes an equilateral shape.

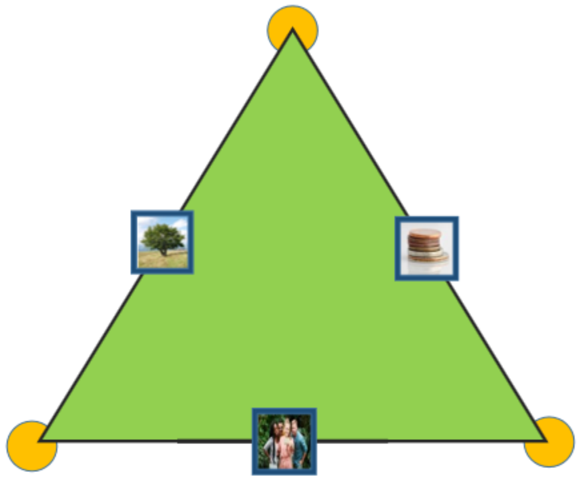


Fig. 1 The sustainability concept.

2.2 The CE and TD Concept/Principles

CE has become part of our everyday life. Figge et al. [4] widely discuss the several definitions of CE that are prevalent in literature, and concluded with a possible definition based on the following four principles:

- The resource cycles in perfect CE are clearly closed, negating the utilization for virgin resources.
- Resource flows must be optimized so that outputs and inputs are equal (meeting of supply and demand).
- CE is distributed across two complementary loop levels: cluster of firms/industries (1st level), single actor/firm (2nd level).
- Perfect circularity is unlikely to emerge due to the TD laws and the inevitability of human errors.

According to the Commission of European Communities [5], CE is "a system where the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste is minimized". This signifies a paradigm shift from "waste" to "product" (Fig. 2), thus requiring that a product is originally designed to promote its durability and reuse.

The colloquial definition of CE tends to be rather oversimplified and limited generally depicted as a full circle for recycling/reuse operations. Yet, CE is a system designed to regenerate itself where all resource loops are not fully closed but inevitably characterized by some losses (Fig. 3a).

Fig. 2 From "waste" to "product": examples.

A perfect CE, therefore, ignores the practicalities of the real world (above principles a and d) and is distributed across two complementary loop levels (principle c), i.e. recoveries within the same or different processes or systems. The challenge is to reduce the losses, and consequently the need of equivalent virgin resources (principle b), thus re-establishing quantitatively, and not merely qualitatively, the overall "mass/energy balance", also considering that the dynamics of recycle flows are substantially different from those of acquiring new resources [6].

Similarly to SD, CE must be seen from a "relative" point of view, because it depends on the local context and the extension of the system boundaries. The greater the extension of the system, defined by the number of linear processes included in the system, the greater the possible circularity of the system "as a whole" [2].

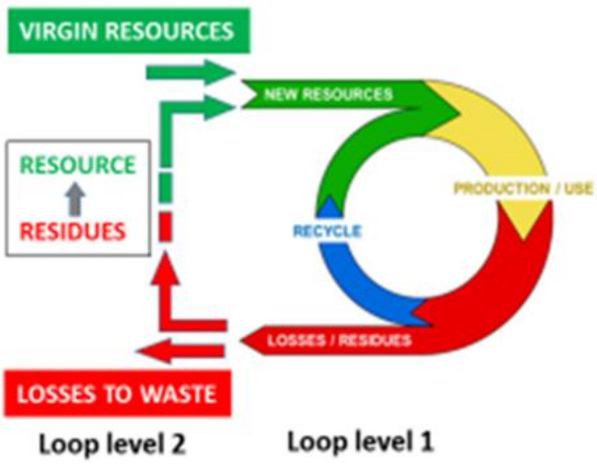
The circle represents the dynamism and cyclicality of perennial time without beginning or end, as demonstrated by the impossibility of measuring its length with a finite number, having instead to resort to an irrational number (π, pi) constituted by an infinite sequence of digits from which only an approximation is obtained.

In practical reality, any production system consists of a series of linear unit processes each represented by one side of an n-sided polygon (e.g. the dewatering operation in sewage sludge management). Furthermore, each process is often divided into relevant sub-processes (e.g., in the dewatering operation, production of conditioning agents, dewatering equipment, transport, etc.) each with its own losses. The greater the number of sides (i.e. individual processes) of a polygon, the closer it approximates to a circle (Fig. 3b).

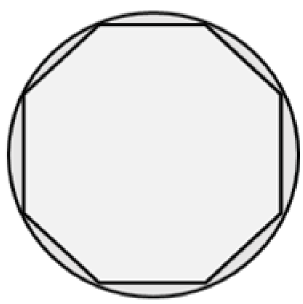
In practice, a process or system can be divided into sub-processes to each of which the CE principles are applied. The greater the number of these processes, the closer it will be possible to achieve a circular system.

However, perfect circularity is unlikely to emerge due to the TD laws according to which all human-operated transformations are "not perfect or fully reversible", thus implying that [6]:

- Energy is invariably conserved, but energy/material losses are always occurring (1st law).
- Entropy, which measures the disorder in an isolated system, constantly increases, so a worse state than before is always involved (2nd law).
- Absolute zero value is impossible, so that perpetual motion, i.e. infinite recycling, is impossible (3rd law).



(a)



(b)

Fig. 3 CE concept.

TD laws are a confirmation that recovery can never be 100% and its level of appropriateness may differ between materials [7]. It follows that human activities will never be able to fully respect the SD and CE concepts, but only to approximate them.

TD can be graphically represented by a square which is a shape that refers to the quadrature of matter, i.e. the concrete realization in space and regularization of what by its nature would have remained shapeless and chaotic. Thanks to the symmetry of the opposite sides, the square conceptually represents the order underlying natural events, such as the four seasons and the four cardinal points.

3. Circularity vs. Sustainability

Understanding the role played by CE in the path towards the sustainability of sludge management systems, in particular the level of response that CE can give to sustainability principles, it is necessary to consider that the practical and effective application of the SD concepts first requires a change in the "Way of thinking" and then the adoption of appropriate "Ways of acting" [2, 6].

3.1 Way of Thinking—The Locomotive Concept

The new "Way of thinking" consists in considering sludge management as the "Locomotive", and not the "Last wagon", of the wastewater system train. Indeed, in traditional approaches sludge generally plays a secondary role in the design of wastewater management systems, since it physically takes place at the end of the water cycle, while the selection of the most appropriate sequence for wastewater treatment is strongly driven by the sludge reuse/disposal options available in the specific local context (geographical, economic, technological, infrastructural, social, etc.) [6].

CE can certainly contribute, from a conceptual point of view, to the practical application of this new way.

3.2 Ways of Acting

The "Ways of acting" consists in adopting appropriate "Technical" actions, aimed at maximizing the benefits of recovery through the reduction of losses and consumption of virgin resources, and "Institutional/Governance" actions to consider the social and regulatory aspects.

3.2.1 Technical Actions

Many treatments or processes can be adopted in the context of "Technical actions" but, in any case, (i) the reduction of nuisances and (ii) the reduction of volume represent two unavoidable "Hubs" in the journey of the sludge from origin/production to destination (Fig. 4) [8].

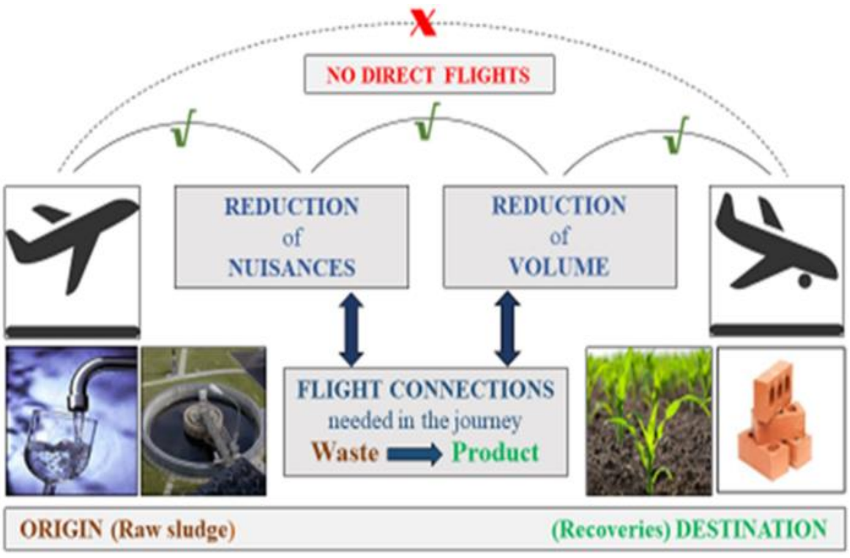


Fig. 4 Technical "hubs" in sludge processing from origin to destination.

The “Reduction of nuisances” is linked to the improvement of quality mainly through stabilization and digestion processes that also involve a reduction in the putrescibility of organic substances and a certain level of inactivation of pathogenic microorganisms.

The “Reduction of volume”, through thickening and dewatering processes, allows obtaining the most suitable solids concentration, volume, and physical consistency (liquid, paste-like, or solid) for the intended use. The objective is not to push production towards an absolute minimum but, instead, to make the sludge amount compatible with its actual destination, including transport and storage steps, and the best overall energy/material balance [9].

The application to technical actions of the principles on which CE is based, i.e. from waste to product, reduction of losses and less use of virgin resources, could allow sustainable solutions which, however, are not always adequate from a social point of view. As a matter of fact, if some technical choices respond to the concept of CE in a certain context, they might not be satisfactory in another context due to inadequate specific local circumstances, e.g. the availability of qualified personnel, lack of infrastructure, and other social barriers.

This means that institutional and governance aspects must also be considered in addition to purely technical ones.

3.2.2 Institutional/Governance Actions

Both regulatory issues, with the associated activities, and issues more specifically linked to social and institutional aspects, addressed to overcome certain barriers, fall within this framework. From this point of view, a sustainable sludge management system should require [3, 6]:

- development of realistic and enforceable regulation supported by the definition of standardized characterization procedures and guidelines of good practice;
- development of approaches tied to specific local circumstances, including the availability of skilled personnel, adequate infrastructure, cultural priorities and other social aspects;
- elimination/reduction of barriers towards accessing waste, wastewater and sludge systems.

The development of realistic and enforceable regulation is crucial because an environmentally safe waste management can only be achieved through objective, transparent, and legally conducted operations. It must be emphasized that regulatory institutions (i) cover a wide range of scales, from national to regional and local ones, and (ii) include different sectors of law, such as those related to water, health, agriculture, planning and building. Within this framework, regulation should (i) include clear rules for penalties and sanctions, which need to be adapted to the local context, and (ii) avoid imposition of generic and/or unjustified limits.

Furthermore, regulation needs to be supported by “standardized characterization procedures” and/or “guidelines of good practices” because only well-defined procedures allow legal requirements to be fulfilled in a correct and uniform manner, thus building stakeholder and public confidence.

Endogenous factors (e.g. taboos towards waste, rural/peri-urban/urban areas, formal or informal settlements, etc.) and exogenous factors (e.g. limited access to public systems, water scarcity, lack of viable infrastructure, socially disadvantaged groups, or low-income households, etc.) can hinder access to waste, wastewater and sludge systems, thus making it difficult to develop sustainable systems.

The coexistence and/or overlap of rules at multiple levels and with different origins and legitimation (termed as legal pluralism), as well as the gap between rules and individual behaviours constitute further factors that hinder the development of sustainable systems. Therefore, rules and regulations need to be evaluated carefully, also considering enforcing mechanisms.

It is undeniable that the difficulty in identifying objective and reliable evaluation or measuring parameters for social issues constitutes, contrary to what is possible for economic and environmental issues, a limitation of the role of the CE regarding sustainability. In essence, this translates into the fact that the evaluations of social aspects are less robust than economic and environmental ones.

4. Integrating SD/CE/TD

Given that the management of sludge/biosolids, as the final product of a water/wastewater treatment system, must constitute the "Locomotive" for a sustainable management of the entire wastewater treatment train, the CE principles are, together with those of TD, a necessary condition for the sustainability of such a complex system.

As previously told, the three SD aspects can be represented by an equilateral triangle (light green in Fig. 5).

Even though cycles in CE are not completely closed, but inevitably characterized by some losses and need of virgin resources, the rules of geometry demonstrate that only one circle (blue in Fig. 5) passes through three non-aligned points, so EC can conceptually play the role of bridging the principles of SD.

However, taking into consideration that the social dimension of sustainability usually remains poorly addressed in CE and possibly inadequate to specific local circumstances, triangle (dark green in Fig. 5) is not going to be equilateral because the side representing the social aspect is possibly shorter than the other sides representing economic and environmental/ecological factors.

A specific local social and institutional framework may require the adoption of technical solutions that could be not optimal from the exclusive CE point of view to identify a sustainable solution in that context. For example, a longer life cycle of a specific component of the system could lead to a reduction in labour and/or an increase in costs with unacceptable consequences from a social point of view.

As told, perfect circularity is unlikely to emerge due to TD (red square in Fig. 5) so, in reality, circularity can only be addressed with a series of linear processes converging into a circular system or, in other words, approximating a circle with a polygon of n sides (whose perimeter can be calculated in a finite way): the greater the number of sides, the greater the approximation to a circle.

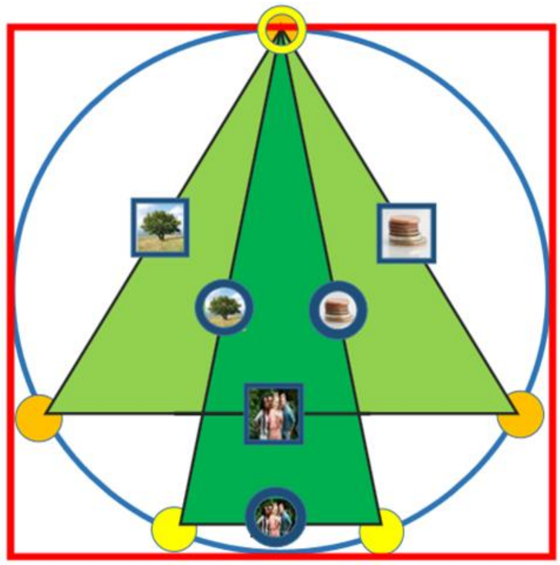


Fig. 5 Integrating SD/CE/TD principles.

In summary, CE acts as a link between the principles of SD and TD, thus allowing, with a view to the SD of a complex system, the adoption of actions that will be all the more effective the more complete the evaluation of the social dimension has been.

5. Conclusions

CE plays a key role to move from the concept of "waste" to that of "product" through the adoption of technologies aimed at [6]:

- keeping products and materials in use (longer life cycle);
- assessing management paths capable of maximizing the recycle/recovery benefits;
- fostering economic growth without increasing environmental pressure;
- developing operational systems appropriate to local and site-specific circumstances;
- adopting multiple options for sludge destination able to be adapted to local market variabilities;

- defining the treatment(s) necessary to optimize the entire system through the development of self-sustaining energy systems, or systems with a low energy environmental impact;
- using technically, ecologically and economically feasible methods to reduce sludge quantity at the appropriate level, and not necessarily to the minimum one.

Above actions could allow providing adequate solutions for the adoption of actions aimed at sustainability, also having to consider that, due to the principles of TD, human activities can only approximate the sustainability and CE principles.

However, technical choices theoretically responding to the CE concepts in some contexts, could not be satisfactory in other contexts due to inadequate specific social circumstances. This requires issuing realistic and enforceable regulation, availability of qualified personnel, lack of infrastructure, and other social barriers to accessing wastewater and sludge systems [7].

CE represents an important approach for guarantying the sustainability of a production cycle or system, provided that the social dimension of sustainability is considered at an adequate level. This is a notable limitation to the CE concept because the evaluation parameters of the economic and environmental aspects are not applicable to the social and governance aspects.

Therefore, CE represents a necessary, but often not sufficient, support for sustainability.

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