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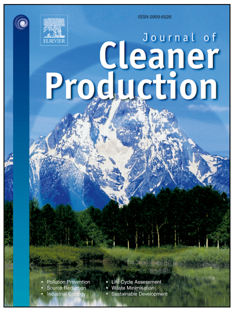

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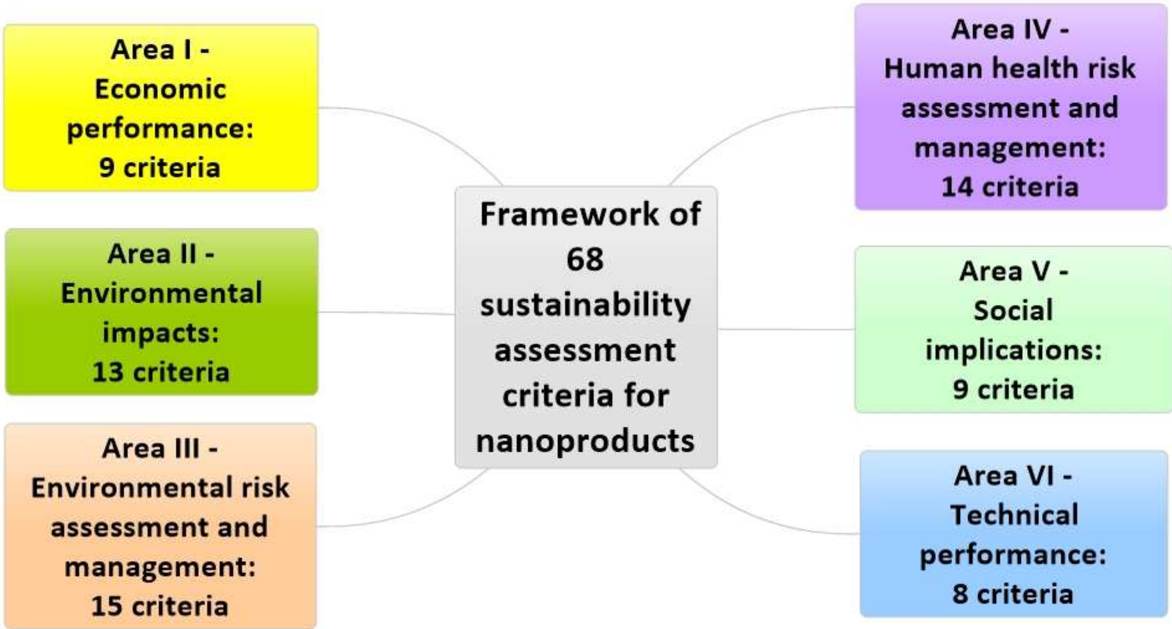
Graphical abstract



A Framework of Criteria for the Sustainability Assessment of Nanoproducts

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ABSTRACT

Nanotechnology applications (nanoproducts) have entered the market or are expected to do so in the near future. Robust and science-based criteria are required to appraise and manage their sustainability. This paper describes the approach used to develop a comprehensive and reliable framework of criteria, which was missing until now, for evaluating the sustainability of nanoproducts. A literature review of the frameworks and tools employed to assess nanoproducts sustainability implications was firstly performed to select an initial set of criteria. A survey of experts in the sustainable nanotechnology domain was then conducted to elicit their knowledge in terms of completeness, reliability and validity of the criteria set. Ranking and correlation analyses completed the research by identifying the parameters of major interest as well as the links and dependencies between them. A total of 54 and 65 experts replied to the pilot and main survey, respectively. The reliability and validity of the criteria was assessed with the responses from both questionnaires, whereas the answers from the main survey were used to calculate the relative index of the criteria as well as their correlations. This research resulted in a framework composed of 68 criteria, which are structured into six main areas: (i) economic performance; (ii) environmental impacts, (iii) environmental risk assessment; (iv) human health risk assessment; (v) social implications and (vi) technical performance. This study helps to broaden the understanding on the identification of criteria for sustainability assessments. It also provides those interested in evaluating nanotechnology implications with the basis for real case studies, possibly by integrating available information with the stakeholders using tools that support decision-making.

Keywords: sustainability assessment; decision-making; nanoproducts; nanotechnology; criteria; survey.

1. Introduction

Nanotechnology is emerging as one of the next industrial revolutions, enabling enhanced functionality of current materials as well as creating new products in a broad set of application areas, including environmental remediation, UV filters, energy production, hydrogen storage, composites reinforcements and drug delivery (Roco et al., 2011; Shapira and Youtie, 2015). For this reason, the assessment of the implications of nanoproducts (NPs)[1] must be accounted for in order to guarantee a responsible and sustainable development of this technology (Eason et al., 2011; Subramanian et al., 2015).

Green and sustainable nanotechnology is mainly focused on the application of the principles of green chemistry (Anastas and Warner, 1998) and sustainability throughout the whole life cycle of NPs (Hutchison, 2008; Karn, 2008; Subramanian et al., 2014). The highest levels of acceptance and benefits for society can be achieved if technological development of nanotechnology is coupled with the evaluation of societal, environmental and economic impacts, posing the basis for comprehensive sustainability assessment of different NPs with the same functionality (Bauer et al., 2008; Karn, 2011; Subramanian et al., 2015).

The health and safety concerns NPs raised due to their unique physicochemical properties drew initial attention to their sustainability implications (Beaudrie et al., 2014; Boholm and Arvidsson, 2014; Grieger et al., 2015). A lot of research was then conducted to evaluate the impacts of NPs on sustainability, including life cycle assessments (Miseljic and Olsen, 2014; Upadhyayula et al., 2012), economic and social impact assessments (Dobon et al., 2011) and broad development of criteria sets for a variety of risks, benefits and sustainability implications (Moller et al., 2012; NanoKommission, 2011; Som et al., 2014). What is more it was also shown that integration of available sustainability information on NPs with multiple criteria decision aiding/analysis (MCDA) methods can improve comparability and evaluation of nanotechnology outputs (Cinelli et al., 2015; Linkov and Moberg, 2012).

The adoption of sustainability principles for nanotechnology can contribute to overcoming the burden of current unknown risks and since the development of many NPs is still in its infancy, this is a good opportunity to implement changes (Matus et al., 2011; Schmidt, 2007). The evaluation of the implications of nanotechnology is necessary to avoid that a limited number of “unsafe” NPs

[1] Following the approach adopted by (Moller et al. 2012) the term nanoproduct used in this paper refers to nanomaterials per se and products containing such materials.

can cause a backlash against the whole nanotechnology area, implying that public information and awareness will play a great role in the acceptance of this new technology too (Eckelman et al., 2008; Malsch et al., 2015). As a consequence, the measurement of sustainability of NPs is essential to steer its development in a responsible and ethical direction.

In order to perform accurate evaluations of sustainability of NPs it is necessary to develop holistic frameworks that can cover a comprehensive set of sustainability implications. The attainment of this goal is possible only if a clear problem structure is first performed, starting from the identification and formulation of a reliable and inclusive group of sustainability criteria (Bottero et al., 2015; Cinelli et al., 2013; Dias and Domingues, 2014). Until now a criteria framework was not available for the sustainability assessment of NPs (Mata et al., 2015; Moller et al., 2012; Subramanian et al., 2015) and this paper describes the approach that was implemented to fill such research gap.

2. Materials and methods

The development of the framework of sustainability criteria for NPs followed a 3-stage approach. It included literature review (1st research stage) for identification of an initial set of criteria, the development of a pilot survey (2nd research stage) to test the appropriateness and validity of the criteria and the main survey (3rd research stage) to confirm the reliability and validity of the criteria. Questionnaire was used as a research method since it allows eliciting quantitative description of trends, opinions and attitudes from a sample of a certain population (Creswell, 2014).

2.1 Sustainability criteria for nanoproducts

Assessment criteria are one of the fundamental components of any sustainability evaluation (Cinelli et al., 2014; Dias and Domingues, 2014; Singh et al., 2012). Drawing from the approach adopted in the MCDA literature (Greco et al., 1998) the term criterion used in this paper is intended as a condition attribute that is employed to characterize and also assess the nanoproducts. More specifically the criteria represent factors that can be used to make a judgment about the relative sustainability of a set of alternatives (Foxon et al., 2002).

In order to identify and develop the sustainability criteria of NPs, the frameworks and tools employed to assess their sustainability implications were reviewed to map the areas that received most attention (1st research stage). The literature search was performed using web of science[2] and Google Scholar[3] database with a combination of the keywords “nanotechnology”, “sustainability”, “economics”, “environment”, “risk assessment”, “regulation”, “impacts”, “potentials”, “risks”, “benefits”, “implications”, “opportunities”, “threats” and “concerns”.

The strategy used to identify and shape the criteria followed published guidelines (Akadiri and Olomolaiye, 2012; Akadiri et al., 2013). The details about the selection procedure and the explanation of the criteria can be found in Appendix A and B in supplementary information. The criteria selected as a starting list for NPs sustainability assessment have been grouped in six main areas, in order to clearly distinguish along established research themes. Sustainability is generally accepted to have three pillars (Elkington, 1999). Economic performance was identified as an area by itself (*framework area I*), whereas the environment was split into two areas, one referring to the environmental impacts (*framework area II*) caused by the NP during its lifecycle, while the other targeting the environmental risk assessment and management (*framework area III*). In a similar fashion, societal issues were divided in two major themes; the human health risk assessment and management (*framework area IV*) and the broader ethical, legal, governance and social implications (*framework area V*). Lastly the area of technical performance (*framework area VI*) completed the domains of research. The latter was included in the framework of sustainable nanotechnology since the emergence of NPs is strictly dependent on the performance of such goods when compared to conventional products (Meyer and Upadhyayula, 2014) and are only likely to enter the marketplace if they perform as well or offer additional benefits. As a consequence, products that do not meet technical specifications would not even be considered for production, which would render any effort to identify sustainability criteria in other areas worthless (Moller et al., 2012).

2.2 Survey development

The survey (Appendix C and G in supplementary information) was developed to collect the following information from the respondents:

- Specification of professional expertise and geographical area of operation;

[2] http://apps.webofknowledge.com/UA_GeneralSearch_input.do?product=UA&search_mode=GeneralSearch&SID=Y1QNdlRWvXzqtJ8ifGs&preferencesSaved=

[3] https://scholar.google.com

- Evaluation of importance of each criterion in relation to the assessment of implications of NPs in the area of concern (on a 5-point Likert scale from very low to very high);
- Addition of missing criteria and comments.

The questionnaire was developed as an online assessment through the software Questionmark Perception,[4] licensed to the University of Warwick, UK.

2.2.1 Pilot survey

Comprehensibility and feasibility of the questionnaire was assessed through piloting (2nd research stage), which was conducted to test the appropriateness of the questions wording, the reliability and validity of the criteria used in each area and to include further criteria that might have been excluded during the literature review (Bourque and Fielder, 1995). In this research stage the respondents' sample was composed of key informants in the areas of nanotechnology and assessment of its sustainability implications (see Appendix D in supplementary information for selection strategy of experts). Such a tactics was adopted since expert opinion analysis is regarded as an excellent tool for investigation of unstructured knowledge (Amer and Daim, 2013) and it was successful in tackling similar issues related to the safety of NPs (Berube et al., 2011; Besley et al., 2007; Choi and Ramachandran, 2009).

The results from the pilot survey were used to modify the main questionnaire by:

- improving accuracy;
- re-wording of questions;
- adding criteria.

The improvements satisfied the requirements for questionnaires development (Bourque and Fielder, 1995; Gray, 2004) which entitled the submission of the questionnaire in its final version.

2.2.2 Main survey

The main survey (3rd research stage) was conducted with the collaboration of the only organization that gathers people working worldwide in the area of sustainable nanotechnology, the Sustainable Nanotechnology Organization (SNO)[5] as well as the Nanotechnology Knowledge Transfer Network of Innovate UK (Nano-KTN).[6] The final questionnaire was submitted to the members of these organizations. Criteria reliability and validity were firstly assessed. Secondly the

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[4] http://www2.warwick.ac.uk/services/its/servicessupport/eassessment/perception
[5] http://www.susnano.org/
[6] https://connect.innovateuk.org/web/nanoktn

relative ranking of the criteria was derived and lastly the correlations between the criteria were investigated.

2.2.3 Recruitment of participants

The recruitment of participants took place in three stages, both for the pilot and the main survey:

- Firstly an email with a cover letter explaining the background of the project was sent to each expert providing a link to the online survey;
- A reminder email was sent ten days after the first email;
- Another reminder email was sent ten days after the first reminder.

The results were collected through the online platform of Questionmark Perception, stored in Excel files and analyzed with SPSS software[7] version 22, operating with the extension bundle developed to handle ordinal data analysis (Basto and Pereira, 2012).

2.3 Data analysis

The information obtained from the questionnaire consisted of primarily nominal and ordinal data. As far as ordinal data is concerned, it comprised five preference-ordered categories from very low (1) to very high (5), with the addition of the "I do not know" option. Likert-type replies are thus the major components of the results, which do not allow for parametric statistics, unless "precarious and, perhaps, unrealistic assumptions are made about the underlying distributions" (Siegel and Castellan, 1988). On the contrary, ordinal data type is well suited for non-parametric statistical tests, which is ideal for rank-ordered scales (as Likert-type is) (Braimah and Ndekugri, 2009; Field, 2011; Siegel and Castellan, 1988).

The analysis of the replies from the respondents included descriptive statistics, reliability assessment through ordinal alpha, content validity, relative index and correlations analyses.

2.3.1 Descriptive statistics

Descriptive statistics were used to describe the background of respondents who participated in the survey, their length of practice in the area(s) and their scale of operation on a four-choice base (i.e. local, national, supranational and global).

[7] http://www-01.ibm.com/software/uk/analytics/spss/

2.3.2 Reliability assessment

The reliability of criteria scales was assessed by means of ordinal alpha (α) coefficient, a parameter proposed by Zumbo and colleagues (Zumbo et al., 2007) as the appropriate measure to be used with ordinal data (Basto and Pereira, 2012; Gadermann et al., 2012). Ordinal alpha scale goes from 0 to 1 and values greater than 0.700 are usually required to indicate acceptable internal consistency, but scores above 0.800 are preferable (Gadermann et al., 2012; Pallant, 2011). Items that correlate low (under 0.300 as a rule of thumb) or even negatively should to be deleted or the relevant question(s) rephrased (Furr, 2011a; Litwin, 1995), as the reliability tests indicate that they are not measuring the target scale.

2.3.3 Validity assessment

Validity is another mandatory component of survey evaluation as it indicates whether the scale measures what it is supposed to measure (Litwin, 1995). In this questionnaire content validity of the scales was assessed by asking two specific questions to the respondents, whether there were any missing criteria and if there were any doubts about the clarity and organization of the questionnaire (Furr, 2011b).

2.3.4 Relative index

Priorities in the criteria lists were derived by means of relative index (RI, equation 1), which was used to aggregate the scores rated on ordinal scales and derive rankings for the criteria. RI allows identifying the most important parameters based on participants' replies and it is an appropriate tool to prioritize indicators rated on Likert-type scales (Akadiri and Olomolaiye, 2012; Chinyio et al., 1998).

The formula of the relative index is the following (Braimah and Ndekugri, 2009):

$$\mathrm{RI} = \sum_{i=1}^{i=5} \frac{w_i f_i}{N} \quad (1)$$

where w_i is the weighing factor obtained from dividing the rating score by the highest score (i.e. 5), f_i is the frequency of responses and N is the total number of responses. RI scale is [0-1] with 1 indicating the highest importance level.

Furthermore, importance levels were assigned to the criteria on the basis of the value of RI according to this qualitative approach: first, second and third sub-group of parameters.

2.3.5 Correlations between criteria

The correlations between the criteria have been assessed by means of Gamma coefficient (γ, equation 2), which is a measure of association for ordinal variables (Babbie et al., 2013; Sarantakos, 2007). Its value derives from the assessment of paired observations of the variables and is calculated as follows (Babbie et al., 2013):

$$\text{Gamma}, \gamma = \frac{\text{SOP} - \text{IOP}}{\text{SOP} + \text{IOP}} \qquad (2)$$

where SOP stands for "same order pairs", and IOP stands for "inverse order pair". Gamma values vary between − 1 and + 1, with values close to 0 indicating lack of correlation between the variables and values close to $|1|$ indicating strong positive (+ 1) and negative (− 1) correlation between the variables. The threshold limit of $\pm$ 0.5 (or higher whenever indicated) was used as an indication of a substantial/strong relationship between two variables (Babbie et al., 2013; Sarantakos, 2007).

3. Results and discussion

A total of 54 and 65 experts replied to the pilot and main survey, respectively, covering one or more sustainability areas. The reliability and validity of the criteria was assessed with the responses from both questionnaires, whereas only the answers from the main survey (i.e. 65) were used to calculate the relative ranking of the criteria as well as their correlations, in compliance with research guidelines (Bourque and Fielder, 1995).

3.1 Pilot survey

The individual replies received for the pilot survey covered one or more sustainability areas, varying from 9 to 17 per area (Table 1).

Table 1: *Summary of pilot survey results for each individual sustainability area (*: RAM = risk assessment and management)*

These results have been used to assess the completeness, reliability and content validity of the questionnaire. Table 1 show that out of the six areas under investigation the reliability is good or very good for five of them, with the exclusion of economic performance. The comments from the respondents have been important to increase the clarity of the questions and to add the parameters that had not been accounted for. Furthermore, the statistical tests and the respondents' comments were necessary to understand what criteria had to be rephrased or removed and the reasons for such choices.

Table 2: *Changes applied to main survey based on responses of pilot survey*

A summary of the changes that were applied following from the pilot results are presented in Table 1 and Table 2, while details can be found in Appendix E and F of supplementary information. Final survey is in Appendix G.

3.2 Main survey

The experts' knowledge conveyed by the main survey was used to develop a framework of 68 criteria spread across the six sustainability areas, which achieved a good or excellent level of reliability (confirmed by the ordinal alpha coefficient, α) as Figure 1 shows. For each one the relative ranking of the criteria together with their correlations were calculated by relative index (equation 1) and gamma coefficient (equation 2). The next sections focus on the most relevant results from a sustainability assessment perspective (Appendix H provides participants' comments).

Figure 1: *Framework of sustainability assessment criteria for NPs, main survey results (α = reliability of scale; N = number of replies)*

3.2.1 Economic performance

The economic viability of processes that involve NPs manipulation (ECON 1) ranks at the top and it correlates with raw materials costs (ECON 4) Table 3, confirming the importance that a stable market for materials prices has to foster economic sustainability of NPs (Karn, 2011). This consideration is of remarkable importance for nanotechnology as there are various rare earth materials (e.g. gallium, germanium, tellurium) that are crucial in the development of NPs and suffer from limited availability and almost monopolized offer, which is subject to unpredictable prices fluctuations and consequently limited raw materials costs stability (Karn, 2011).

Collaboration embedment among various actors in the value chain (ECON 2) emerges as a very important parameter since nanotechnology business is cross-sectorial, it depends on multidisciplinarity and it necessitates integration of several types of organizations such as university spin-offs, start-ups and small and medium enterprises (SMEs) (Shapira and Youtie, 2012). This type of development needs to find financial support, which is confirmed by the strong correlation between this criterion and the funding trend available for research, development and application of a NP (ECON 3), thirdly ranked in this domain.

Table 3 : *Importance level (IL), relative index (RI) and correlations of economic performance criteria (N is between 4 and 5)*

Raw materials (ECON 4) and manufacturing costs (ECON 5) occupy the fourth and fifth positions respectively in terms of relative importance, they are very highly correlated and a lot of literature confirms this, indicating that such costs are major interlinked players for investors and developers of this emerging technology (Duran et al., 2011; Shapira and Youtie, 2012; Spence et al., 2011).

Public perception of NPs and the funds required by companies to influence it (ECON 6) constitute another reliable aspect to be accounted for the economics of NPs. Customers can affect the success or failure of a NP, as they have the power of choosing whether to buy or not a certain good on the basis of the available and accessible information about it.

Lastly external social costs that society has to bear for health and welfare maintenance (ECON 7) and remediation and conservation of ecosystems (ECON 9) are relegated to the least important level, probably because of the current unreliability and limited applicability of human health and environmental costs monetization techniques (Shapira and Youtie, 2012).

3.2.2 Environmental impacts

Use and production of hazardous materials (ENVIMP 1) tops the ranking for the environmental impacts area (Table 4). Hazardousness of materials is a complex concept that requires integration of a wide variety of characteristics of the materials, including flammability, toxicity, mobility in different environmental compartments, tendency to agglomerate, biodegradation resistance, bioaccumulation and large-scale impacts on the environment such as climate change caused by greenhouse gas emissions (Robichaud et al., 2005; Upadhyayula et al., 2012; van Lente and van Til, 2008).

Risks for resources availability (ENVIMP 11) shows strong correlations with the use of raw (ENVIMP 10) and rare materials (ENVIMP 9), as well as the hazardous materials used and produced (ENVIMP 1) and the waste generation along the life cycle (ENVIMP 2). With the increasing request for materials to produce NPs (Chen et al., 2013) the organization of the supply chains will become a pressing issue in the near future, particularly those with a regional concentration of mining, with constrained physical offer and with structural and technical burdens that could limit the widespread availability of relevant resources.

From a large scale production perspective the waste production during the life cycle of a NP can have huge impacts on the environment, specifically in cases where hazardous materials have been employed (Hutchison, 2008; NanoKommission, 2010b; Theis et al., 2011). Furthermore, several nanomanufacturing processes have very low materials efficiency, which causes high amounts of waste generation in relation to the end product (Reijnders, 2010; Şengül et al., 2008; Upadhyayula et al., 2012). These major environmental concerns find confirmation in the survey, where the waste generation criterion receives the second place rank.

Table 4: *Importance level (IL), relative index (RI) and correlations of environmental impacts criteria (N is between 18 and 22)*

The trend for resources demand (ENVIMP 5) and the use of renewable feedstocks (ENVIMP 4) are highly correlated and complete the first importance level group. In addition the latter (ENVIMP 4) is linked with the energy used during the life cycle of a NP (ENVIMP 8) and the use of local resources (ENVIMP 12). These results suggest that the future of sustainable nanotechnology with limited environmental implications has to rely on an interlinked management system where the controlled development of local renewable resources demand is combined with reduced energy consumption and highly energy and materials efficient processing along the life cycle.

3.2.3 Environmental risk assessment and management

Knowledge about the environmental exposure to a NP (ERAM 1) is the first criterion, whose high rank is justified by the fact that there is currently no knowledge about actual concentrations of NPs in environmental media mainly due to the lack of appropriate measurement techniques (OECD, 2014a). Bioaccumulation (ERAM 2) and agreed-upon tests for transformation, degradation and persistence of target object (ERAM 3) share the second position and the knowledge about the ecological hazard assessment based on the current information (ERAM 4) ranks fourth while biodegradation (ERAM 5) completes this major important criteria set. All these parameters correlate strongly as reported in Table 5, showing the crucial importance that experts in this area report for the need of investigating the interdependent mechanisms that cause NPs modifications in the environment and the realistic exposure concentrations. Studies are required to evaluate the behaviour of a NP once it is released in the environment, especially how and if it is degraded, what paths characterize its exposure to organisms, how it can cross cell membranes and in what matrices and tissues it can accumulate (Baun et al., 2008; Gunsolus et al., 2015; Hou et al., 2013).

The hazard assessment based on current scientific knowledge (ERAM 4) ranks high due to the pressure for the identification of the eco-toxic principle, currently not agreed-upon due to the lack of understanding of toxic behaviour of NPs and relevant measurement techniques (OECD, 2014a, b; Upadhyayula et al., 2012).

The need for adapting the exposure modeling tools (ERAM 6) to tackle NPs uniqueness is the first parameter of the second importance sub-group and it is also correlated with all the higher ranked criteria (Table 5). A possible improvement in this direction is the inclusion of parameters for the actual environment the NP can get in contact with (e.g. ionic concentration, the organic carbon content, pH, fulvic acid concentration) (Hischier, 2014; Labille et al., 2015).

***Table 5:** Importance level (IL), relative index (RI) and correlations of environmental risk assessment criteria (N is between 19 and 22; Discrimination threshold for criteria correlations was raised to 0.6 in order to aid data management)*

Applicability of the eco-toxicity tests (ERAM 7), the agreement on physicochemical properties for such testing (ERAM 8), the possible use of alternative testing strategies (ATS, ERAM 9) and the agreement on assessment endpoints (ERAM 10) are widely linked and complete the second importance sub-group (Table 5). Eco-toxicity testing methods for NPs are a topic of debate since there is still limited scientific information about the interactions mechanisms of NPs with living systems, the influence of aggregation and agglomeration phenomena on NPs' physicochemical properties, the effects of different environments on their reactivity and the assessment endpoints for eco-toxicity testing (Hristozov et al., 2014; Labille et al., 2015; OECD, 2014b). In order to aid the categorization of nanomaterials risk potential, ATS to NPs can be a viable solution, with a recent categorization system having been proposed to support preliminary grouping of NPs to screen those of concern (Godwin et al., 2015).

3.2.4 Human health risk assessment and management

Exposure of humans to the NP (HRAM = 1) and risk management and communication strategies (HRAM 2) are the first criteria in this area and they are highly correlated (Table 6), confirming that these assessments can be accurately conducted only if information on the exposure is known and reliable. The achievement of such objective is hindered by the lack of agreement on the properties of interest from a nanotoxicological perspective (e.g. mass, particle number, surface area, surface charge, particle size distribution), which hampers the development of appropriate exposure measurement as well as health protection equipment and techniques (Brouwer et al., 2012). Nonetheless, systematic process design has been confirmed as an effective approach for reducing workers' exposure to NPs (Fleury et al., 2013; Silva et al., 2016).

The development of an agreed-upon definition of NP (HRAM = 3) is ranked third, confirming its priority both from a risk assessment and a regulatory perspective, including the properties needed for the characterization (Brouwer et al., 2012), which would help harmonizing the vocabulary among practitioners in various parts of the world and help regulatory processes.

ATS for human RA (HRAM = 4) is strongly lined with the agreement on physicochemical properties for toxicity testing (HRAM = 7) as well as the endpoints agreement (HRAM = 9), underlying how these congruities are a necessity, not only to guarantee reliability of the approaches but also the comparability of the results (Hristozov et al., 2014).

As far as the applicability of toxicity testing protocols is concerned (HRAM = 5), OECD test guidelines are considered to be applicable to NPs, although additional properties that should be addressed are presence of impurities, surface functionalisation, nanomaterial changes during storage conditions, chemical composition of the media (i.e. ionic strength, calcium concentration and hardness, pH, dissolver organic matter) and samples characterization prior to administration (e.g. volumes used, sonication times) (OECD, 2012).

Table 6: *Importance level (IL), relative index (RI) and correlations of human health risk assessment and management criteria (N is between 17 and 18; Discrimination threshold for criteria correlations was raised to 0.7 in order to aid data management)*

The group with the least important criteria includes two that are strongly correlated and still characterized by fervent discussion among practitioners, namely the agreement on dose metric for hazard characterization (HRAM = 10) and the agreement on the effective concentration for adverse biological effects (HRAM = 14). In the face of uncertainty NP number, surface area and mass are indicated as properties to be measured for the dose-response analysis (OECD, 2012). The relevant dose depends also on the assessment endpoints to be selected (HRAM = 9), which must be agreed and standardized to guarantee results comparability. The strong correlations between these parameters confirm such viewpoints (Table 6).

3.2.5 Social implications

NPs are used nowadays in a wide variety of applications and consequently they affect society on a multitude of levels. In order to render this process as responsible as possible the legislation has to be efficient, effective and appropriate (Hansen, 2013). This priority finds confirmation in the responses from the experts, rating the regulatory compliance of NPs at the top (Table 7). In order to achieve this objective there are priorities that need attention, including (i) development of methods that are relevant, sensitive and accurate for specific measurands (e.g. number, size, surface area, volume); (ii) tailoring statistics appropriate for the measurand and its uncertainty; and (iii) adopting well-understood and harmonized vocabulary (OECD, 2014b).

The potentials of nanotechnology to support tackling major problems that humanity faces ranks second (SI = 2), in fact nano-enabled applications are under evaluation for example in the areas of pollutants degradation, pollutants monitoring and energy production (Changseok et al., 2013; Jie et al., 2013; Panagiotis et al., 2013).

NPs can cause risks not only from a toxicological standpoint, but also from a broader societal perspective, considering that nano-enabled applications are developed for military purposes (SI = 3) (Kermisch, 2012; NanoKommission, 2011; Türk et al., 2008), an unquestionable matter of ethical controversy (Altmann, 2004; Malsch, 2013). An interesting link emerges in Table 7 between this criterion (SI = 3) and the one referring to the contribution that NPs can make in collecting personal data or tracking individual behavior (SI = 5). Products enabled through nanotechnology can aid retrieving highly sensible personal information that might support military operations, such as espionage activities, terrorism control or more precise targeting (with less collateral damage) (Dalton-Brown, 2012).

Another criterion that received a relatively high position is the promotion of health via NPs (SI = 4). Nanomedicine is a main branch of nanotechnology with huge number of applications in use or under development, from nanodrugs to high-resolution microscopes (Nyström and Fadeel, 2012).

In the least importance level there is the one considering employment effects determined by the NPs production (SI = 8), a parameter difficult to measure due to the huge complexity that underpins the understanding of the number of jobs that are created directly and indirectly as a result of a certain NP (Brignon, 2011; NanoKommission, 2011; Shapira and Youtie, 2012).

Table 7: *Importance level (IL), relative index (RI), and correlations of social implications criteria (N is between 9 and 12)*

3.2.6 Technical performance

Characterizing NPs in a reproducible manner (TI = 1) and manufacturing them with reliable properties (TI = 3) stand at the summit of importance levels for the technical performance scale, with a very high correlation too (Table 8). Reproducibility of characterization techniques has a straight effect on the reliability of NPs, driving the quality assurance that nanotechnology has to focus on. Priorities in this regard are the validation of the methods by means of reference materials, including techniques for handling measurement uncertainty.

"Functionality" criterion (TI = 2) also receives a high relative index, supporting the literature that stresses the need of producing NPs that perform a certain function comparable with the one that a product without the nanomaterial does equally (Benjamin et al., 2013; Moller et al., 2012; NanoKommission, 2011). In fact, the tremendous interest in nanotechnology-enabled products has been the improvement in properties that the materials at the nanoscale can determine (Chen et al., 2013).

Table 8: *Importance level (IL), relative index (RI) and correlations of technical performance criteria (N is between 12 and 16)*

The method of NP manufacturing also received a relatively high rank (TI = 4), which is a driving factor for the widespread diffusion of NPs. A plethora of manufacturing methods are currently emerging for NPs, varying for the type of the target object, such as one-dimensional, two-dimensional and three-dimensional and also the type of techniques, bottom-up and top-down (Moller et al., 2012; Roco et al., 2011). Their development stage is largely uneven, with some being available commercially as it is for atomic layer deposition, laser ablation, lithography, while others still at a laboratory phase stage, such as microwave irradiation and electrospinning (Nadagouda et al., 2014; Şengül et al., 2008). The success of failure of most of these methods in the long term will depend on the ability to manufacture products that meet the stringent requirements of reliable functionality and increased processes yield.

"Recyclability" (TI = 5) scores in the middle-importance set in the list and it received a lot of attention in the literature (Prabu and Ramalingam, 2015; Reijnders, 2010; Theis et al., 2011). Potential options to aid the recyclability of NPs are (NanoKommission, 2010a): (i) limiting the number of employed materials, (ii) adopting segregation/modular waste collection, and (iii) minimizing contamination with impurities. Recycling of NPs is seen with concern, because they add complexity to the products which causes additional problems during recycling, both from a technical and economic perspective (Wigger et al., 2014).

4. Conclusions

Developing frameworks of sustainability criteria is a challenge that requires methodological rigour, multidisciplinarity and a holistic perspective. Nanotechnology is an emerging field that cuts across various disciplines and sectors, thus having broad implications on the environment, economy and society. So far a comprehensive and reliable set of assessment criteria for sustainability implications of NPs was missing and this article describes the research that filled such knowledge gap by devising a framework of such criteria trough a 3-stage approach.

An initial list of criteria was first created by reviewing the frameworks and tools employed to assess sustainability implications of NPs (1st research stage). Experts in the sustainable nanotechnology field were then surveyed to test the wholeness, reliability and validity of the criteria using a pilot (2nd research stage) and a main questionnaire (3rd research stage), which received a total of 54 and 65 replies, respectively. The devised research approach resulted in a comprehensive and reliable framework of 68 sustainability criteria for NPs which belong to six main areas: (i) economic performance; (ii) environmental impacts; (iii) environmental risk assessment and management; (iv) human health risk assessment and management; (v) ethical, legal and social implications; and (vi) technical performance.

The research was then extended using the replies from the main survey by identifying the criteria of major interest (through relative index) as well as the links and dependencies (through correlations analysis) between them. The economic performance domain (*framework area I, 9 criteria*) showed as highly important and strongly interrelated the economic viability of manipulation processes involving the NP as well as manufacturing and raw materials costs. An additional aspect of high priority is the collaboration embedment among various stakeholders along the value chain of NPs, especially due to the multi-sectorial nature of nanotechnology.

Assessment of environmental impacts of a NP (*framework area II, 13 criteria*) require particular attention on the organization of the supply chains, especially when hazardous materials are used or produced during these processes, since many have a constrained availability of raw materials, they are thus facing risks for resources availability and they are causing an increase of the environmental stress on localized areas. Waste generation is also a chief priority, mainly due to the low efficiency of processes that involve manipulation of NPs and consequently cause inefficient use of resources.

The third area of the framework is the environmental risk assessment and management (*framework area III, 15 criteria*), with the need for a reliable characterization and understanding of the environmental exposure to NPs emerging as highest importance, a necessity strongly correlated with the capacity to study the interdependent mechanisms that cause NPs modifications once released in the environment. From the eco-nanotoxicity perspective, the use of alternative testing strategies is advanced as a relevant strategy to reduce the whole animal testing with in vitro and in silico approaches to generate data for hazard screening assessment. Furthermore, high ranking is also placed on the identification of the eco-toxic principle(s) of the NP of interest, namely the constituent(s) / measurand(s) that cause the eco-toxic effect.

Reliable assessment of exposure leads the ranking for the human health risk assessment and management area as well (*framework area IV, 14 criteria*), followed and correlated to the risk management measures that can be adopted to mitigate such exposure. From the hazard perspective, the use of alternative testing strategies emerges as an important complementary solution to traditional testing as in the case of environmental RA. Furthermore, in order to guarantee studies comparability and reliable hazard assessment, specific guidance on the samples preparation and dosimetry is confirmed as an incumbent necessity.

Broad ethical, legal and social implications of NPs are covered in the fifth area (*framework area V, 9 criteria*), which sees the role of regulatory compliance of NP as the first prerogative, with three specific needs that include (i) reliable, sensitive and accurate methods for specific measurands, (ii) reliable statistics for such measurands and (iii) an agreed-upon vocabulary for nanotechnology. Other themes of high importance are the applications based on NPs developed to tackle environmental issues, especially for the reduction of technological imbalance between developed and developing countries and the potentially controversial ethical uses of nanotechnology, including weapons production, espionage and privacy violation through sensible data hacking.

The technical performance area completes the criteria typology (*framework area VI, 8 criteria)*, with the quality assurance leading the set, including functionality and reliability of NP together with reproducibility of characterization techniques.

The present study has two limitations that can be seen as proposals for future research. First, the pool of respondents could be expanded by including additional experts in each area of the framework in order to increase the credibility of the results and further verify the completeness, reliability and validity of the criteria. Second, the survey could be structured in order to include the perspectives of other stakeholders such as single individuals, NGOs and governmental agencies, to study which criteria they would consider worthy of analysis.

The framework of criteria proposed in this study can be used to increase the knowledge about the sustainability of NPs. One possibility is the application of the criteria from one or more areas to a single or more NPs. In the first case it is possible to identify a benchmark evaluation for the NP and understand the indicators where it performs poorly and the reasons for that. In the case when multiple NPs are compared (with the same criteria), a relative assessment of sustainability level can be obtained. An important consideration in the implementation of the framework is the lack of complete information on each criterion. A potential solution to this problem is to decrease the quality of the measurement scale for the criteria. For example, it would be possible to switch from a quantitative to a qualitative scale, which requires much less information on the indicators while still providing an indication of the performance of the NP.

Another use that can be made of the criteria consists in developing integrative assessments based on Multiple Criteria Decision Aiding (MCDA) methods, through the aggregation of the information conveyed by each criterion in the form of a comprehensive evaluation of NP sustainability. In this regards, the relative importance of the criteria can be used as preference information to develop ranking and classification models for sustainability assessments of NP.

This study helps widening the understanding on the identification of criteria for sustainability assessments. It also provides those interested in evaluating nanotechnology implications with the basis for real case studies, possibly by integrating available information with the stakeholders using tools that support decision-making.

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Statistics	Economic performance	Environmental impacts	Environmental RAM*
Number of replies (N)	9	16	17
Reliability of scale (α)	0.370	0.883	0.827
Criteria based on literature review	7	13	14
Changes applied following analysis of pilot survey results	2 criteria added	-	1 criterion deleted and 2 added
	Human health RAM*	**Social implications**	**Technical performance**
Number of replies (N)	17	14	14
Reliability of scale (α)	0.781	0.823	0.844
Criteria based on literature review	14	10	7
Changes applied following analysis of pilot survey results	1 criterion deleted and 1 added	1 criterion deleted	2 criteria added

Table 1: *Summary of pilot survey results for each individual sustainability area (*: RAM = risk assessment and management)*

Sustainability area	Changes introduced in the main survey
Economic performance	• Rewording of main introductory question for this area to account for the fact that the criteria are not always about impacts, but rather about conditions for NPs to emerge • Addition of criteria: (i) "*the embedment of collaboration among various actors in the value chain*", and (ii) the business capital investment for *"public perception of NPs"*
Environmental impacts	• The concept of functional unit of the NP was emphasized in the main survey so that selection of importance of criteria is requested in comparison to a non-NP with the same functionality
Environmental risk assessment and management	• Rewording of questions to account for the need of a case-by-case (i.e. NP specific) consideration when indicating the importance of the criteria • Deletion of criterion "*properties extrapolation from non-nanoscale to nanoscale materials*" due to lack of correlation and supportive relevant literature • Addition of criteria: (i) "*use of alternative eco-toxicity testing strategies*" and (ii) "*development of media specific eco-toxicity tests for NPs"*
Human health risk assessment and management	• Rewording of questions to account for the need of a case-by-case (i.e. NP specific) consideration when indicating the importance of the criteria • Deletion of criterion "*properties extrapolation from non-nanoscale to nanoscale materials*" based on expert judgement • Addition of criterion "*use of alternative toxicity testing strategies*"
Social implications	• Deletion of criterion "*added value for users*" due to lack of correlation and consistency with the whole scale of assessment
Technical performance	• Addition of criteria: (i) "*method of manufacturing for the NP*" and (ii) "*reproducibility of NP characterization technique*"

Table 2: *Changes applied to main survey based on responses of pilot survey*

Criteria	IL	RI	Positive correlation	Negative correlation
ECON 1 = Economic viability of NP manipulation processes	I	0.800	ECON 4, 5	ECON 7
ECON 2 = Collaboration embedment among actors along the value chain		0.720	ECON 3	
ECON 3 = Funding trend for research, development and application of a NP		0.720	ECON 2, 6	
ECON 4 = Raw materials costs of NP manipulation processes	II	0.680	ECON 1, 5	ECON 7
ECON 5 = Manufacturing costs for NP		0.640	ECON 1, 4, 9	
ECON 6 = Public perception of NP		0.640	ECON 3, 7	
ECON 7 = External social costs for health and welfare	III	0.600	ECON 6	ECON 1, 4
ECON 8 = Waste treatment and disposal costs		0.550		
ECON 9 = External social costs for remediation-conservation of ecosystems		0.440	ECON 5	

Table 3: *Importance level (IL), relative index (RI) and correlations of economic performance criteria (N is between 4 and 5)*

Criteria	IL	RI	Positive correlation	Negative correlation
ENVIMP 1 = Hazardous materials used or produced	I	0.735	ENVIMP 10, 11	ENVIMP 13
ENVIMP 2 = Waste generation		0.700	ENVIMP 11	
ENVIMP 3 = Water use		0.690	ENVIMP 10, 12	
ENVIMP 4 = Use of renewable resources		0.678	ENVIMP 5, 8, 12	
ENVIMP 5 = Resources demand trend		0.670	ENVIMP 4	
ENVIMP 6 = Materials efficiency	II	0.658	ENVIMP 7	
ENVIMP 7 = Energy efficiency		0.648	ENVIMP 6, 8, 12	
ENVIMP 8 = Energy consumption		0.646	ENVIMP 4, 7, 12	
ENVIMP 9 = Use of rare materials		0.646	ENVIMP 10, 11	
ENVIMP 10 = Use of raw materials	III	0.637	ENVIMP 1, 3, 9, 11	
ENVIMP 11 = Risks for resources availability		0.620	ENVIMP 1, 2, 9, 10	
ENVIMP 12 = Local resources use		0.550	ENVIMP 3, 4, 7, 8	
ENVIMP 13 = Processing conditions		0.545		ENVIMP 4

Table 4: *Importance level (IL), relative index (RI) and correlations of environmental impacts criteria (N is between 18 and 22)*

Criteria	IL	RI	Positive correlation
ERAM 1 = Environmental exposure to a NP	I	0.764	ERAM 2, 3, 4, 5, 6, 7, 12
ERAM 2 = Bioaccumulation of NP		0.717	ERAM 1, 5
ERAM 3 = Transformation, degradation and persistence tests		0.717	ERAM 1, 8, 9
ERAM 4 = Ecological hazard assessment based on current scientific knowledge		0.713	ERAM 1, 5, 8, 11, 14
ERAM 5 = Biodegradation of NP		0.691	ERAM 1, 2, 4, 11
ERAM 6 = Adaptation of exposure modeling tools	II	0.686	ERAM 1, 8, 9, 10, 11, 13, 14
ERAM 7 = Eco-toxicity tests applicability to NP		0.682	ERAM 11, 13, 14, 15
ERAM 8 = Physicochemical properties agreement for eco-toxicity testing		0.675	ERAM 3, 4, 6, 9
ERAM 9 = Alternative eco-toxicity testing strategies		0.666	ERAM 3, 6, 8, 10, 11, 12
ERAM 10 = Agreed set of assessment endpoints for eco-toxicity tests		0.648	ERAM 6, 9
ERAM 11 = Risk quantification based on current scientific knowledge	III	0.635	ERAM 4, 5, 6, 7, 9, 13, 14
ERAM 12 = Media specific eco-toxicity tests		0.630	ERAM 1, 9
ERAM 13 = Applicability of environmental exposure models		0.626	ERAM 6, 7, 11, 14, 15
ERAM 14 = Use of data on close analogues for eco-toxicity		0.600	ERAM 4, 6, 7, 11, 13
ERAM 15 = Agreed-upon definition for a NP		0.582	ERAM 7, 13

Table 5: *Importance level (IL), relative index (RI) and correlations of environmental risk assessment criteria (N is between 19 and 22; Discrimination threshold for criteria correlations was raised to 0.6 in order to aid data management)*

Criteria	IL	RI	Positive correlation
HRAM 1 = Human exposure to NP	I	0.718	HRAM 2, 5, 6, 7, 8, 11, 12, 14
HRAM 2 = Risk management and communication		0.700	HRAM 1, 5, 6, 8, 12, 14
HRAM 3 = Agreed-upon definition for a NP		0.689	HRAM 7, 9
HRAM 4 = Alternative toxicity testing strategies		0.689	HRAM 7
HRAM 5 = Toxicity tests applicability to NP	II	0.678	HRAM 1, 2, 8, 11
HRAM 6 = Links of NP's properties with ADME profiles		0.678	HRAM 1, 2, 7, 8, 14
HRAM 7 = Physicochemical properties agreement for toxicity testing		0.667	HRAM 1, 3, 4, 6, 8, 9, 10, 12, 14
HRAM 8 = Human health hazard assessment based on current scientific knowledge		0.646	HRAM 1, 2, 5, 6, 7, 9, 11, 12, 13
HRAM 9 = Agreed set of assessment endpoints for toxicity testing		0.643	HRAM 3, 7, 8, 10, 11, 12, 14
HRAM 10 = Dose metric agreement for NP hazard characterization	III	0.632	HRAM 7, 9, 14
HRAM 11 = Risk quantification based on current scientific knowledge		0.632	HRAM 1, 5, 8, 9
HRAM 12 = Use of toxicity data of close analogues for target NP		0.632	HRAM 1, 2, 7, 8, 9, 14
HRAM 13 = Properties extrapolation from non-nanoscale to nanoscale materials		0.610	HRAM 8
HRAM 14 = Effective concentration agreement for adverse biological effect		0.567	HRAM 1, 2, 6, 7, 9, 10, 12

Table 6: *Importance level (IL), relative index (RI) and correlations of human health risk assessment and management criteria (N is between 17 and 18; Discrimination threshold for criteria correlations was raised to 0.7 in order to aid data management)*

Criteria	IL	RI	Positive correlation
SI 1 = Regulatory compliance of NP with current and upcoming legislation	I	0.850	SI 3, 4, 5, 6, 7, 9
SI 2 = Tackling environmental issues via NP		0.782	SI 6, 7
SI 3 = Use of nano-enabled products for military purposes		0.764	SI 1, 5, 8, 9
Si 4 = Promotion of health enabled via NP	II	0.682	SI 1, 6, 7, 9
SI 5 = Collection of data and personal behavior via NP		0.673	SI 1, 3, 6
SI 6 = Reduction of nano-divide		0.600	SI 1, 2, 4, 5, 7
SI 7 = Promotion of education and information management via NP	III	0.582	SI 1, 2, 4, 6, 9
SI 8 = Employment effects deriving from a NP production		0.556	SI 3, 9
SI 9 = Symbolic benefits for users		0.435	SI 1, 3, 4, 7, 8

Table 7: *Importance level (IL), relative index (RI), and correlations of social implications criteria (N is between 9 and 12)*

Criteria	IL	RI	Positive correlation
TP 1 = Reproducibility of NP characterization technique	I	0.880	TP 3, 7
TP 2 = Functionality of NP		0.875	
TP 3 = Reliability of NP		0.867	TP 1, 8
TP 4 = Manufacturing method of NP	II	0.772	
TP 5 = Recyclability of NP		0.754	TP 9
TP 6 = Maintainability of NP		0.743	
TP 7 = Technology maturity for NP manufacturing method	III	0.713	TP 1
TP 8 = Durability of NP		0.700	TP 2

Table 8: *Importance level (IL), relative index (RI) and correlations of technical performance criteria (N is between 12 and 16)*

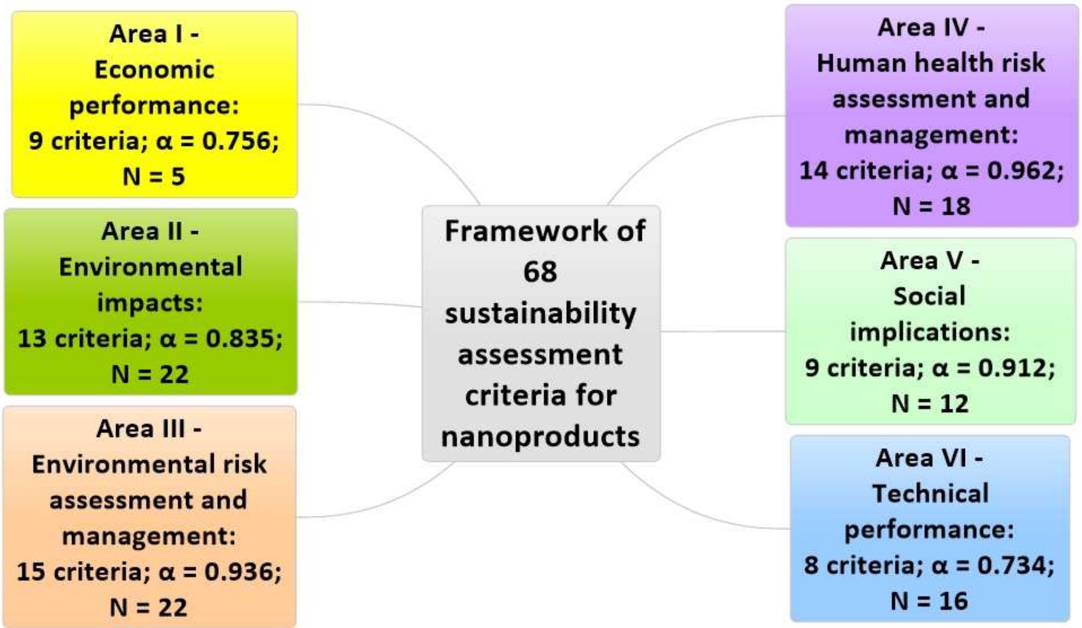

Figure 1: *Framework of sustainability assessment criteria for NPs, main survey results (α = reliability of scale; N = number of replies)*

Highlights –

A Framework of Criteria for the Sustainability Assessment of Nanoproducts

- The knowledge of 119 experts of sustainable nanotechnology was examined.
- A framework of 68 sustainability assessment criteria for nanoproducts is proposed.
- Six main reliable areas of nanoproducts sustainability criteria are advanced.
- A ranking of sustainability assessment criteria for nanoproducts is identified.
- The correlations between the sustainability assessment criteria are also analysed.

Nanoproduct(s) = NP(s)

Economic performance criteria = ECON

Environmental impacts criteria = ENVIMP

Environmental risk assessment and management criteria = ERAM

Human health risk assessment and management criteria = HRAM

Social implications criteria = SI

Technical performance criteria = TP