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The path towards healthier societies, environments, and economies: a broader perspective for sustainable engineered nanomaterials

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Abstract

Economic value is no longer adequate by itself as a proxy for the value-added benefits (VAB) assumed to be generated by emerging technologies such as engineered nanomaterials (ENMs). This study was conducted to explore the potential to establish an integrated sociotechnical framework with the end goal to assess whether or not ENMs and nano-enabled products contribute VAB. Based on the research in this study, it is suggested that all stakeholders in the larger society–environment–economy (SEE) system should develop an understanding of the multiple interrelationships within and between the diverse constituents along the particle lifecycle trajectory to capture their influence on the system benefit and risk outcomes. Furthermore, the sociotechnical framework establishes an additional three-step process: (1) at the pre-design stage, the test of VAB should be assessed using an expert panel representing the different segments of SEE, the social principles of design are detailed and customized to the needs of ENMs and nano-enabled products, and an economic appraisal is conducted to justify the VAB on material grounds; (2) at the design stage, the technical principles should be examined and detailed to ensure the compatibility of stakeholder needs; and (3) an iterative adaptive cycle should be conducted to re-examine the sociotechnical principles on a periodic basis. Within this context, ENMs are considered sustainable when (a) the conditions of VAB and minimal risk elements are satisfied in a sequential order, with VAB demonstrated at the pre-design stage, then at the design stage ENMs posing no harm greater than minimal levels to the SEE constituents; and (b) ENMs and nano-enabled products are bounded by a finite time limit. In addition, to reach the conditions of sustainability, the role of all SEE stakeholders should be broadened (e.g., regulatory agencies should transform their roles from not only the control of risks of negative implications, but also the establishment of positive implications as well).

Keywords

Sustainable engineered nanomaterials; Physical–chemical properties; Value-added benefits (VAB); Green chemistry and engineering; Cognitive engineering; Society, environment and economy

Introduction

There has been a debate in the scientific literature as to whether or not engineered nanomaterials (ENMs) are new chemicals. Although ENMs share common characteristics with their bulk counterparts (e.g., silver ENMs and their bulk counterparts) (Nowack et al. 2011), it has been demonstrated that ENMs have novel properties resulting in unique implications along the particle lifecycle trajectory (Costanza et al. 2011). Thus, major concerns have been raised about ENM sustainability. Within this context, Tolaymat et al. (2015a) suggested that the conditions of sustainability for these materials and products should integrate benefits and risks with time boundaries. They (2015b) also presented an integrated science-based methodology to assess the potential risks of engineered nanomaterials, with the ultimate goal to minimize or eliminate their risks along the particle lifecycle trajectory. In this paper, the issue of value-added benefits (VAB) is investigated within the realms of sustainable nanomaterials.

Two approaches have been in current use to assess whether or not emerging technologies such as ENMs are contributing VAB to the constituents of the larger society–environment–economy (SEE) system. The first approach relies on the classic methodology of benefit–cost analyses (Saez and Requena 2007). The second technique, on the other hand, is based on assessing the needs, wants, and preferences of consumers (Day and Crask 2000). Each approach is complementary to each other in the sense that each methodology is necessary but not sufficient on its own. Furthermore, while the cost–benefit technique is based on monetary and hence quantitative criteria, the consumer preference approach suffers from the lack of analytic criteria designed to assess its value.

Currently, it is hypothesized that adding nano-sized particles to products in lieu of their bulk counterpart contributes VAB to the different segments of SEE due to the unique physical–chemical properties of such materials and their applications to the manufacture of diverse consumer, industrial, and healthcare products (El Naschie 2006; Tolaymat et al. 2010; Sekine et al. 2013; Gebel 2013; Chatterjee 2008). These applications are being marketed as satisfying the unfulfilled needs and wants of SEE constituents from biological entities to natural environments to waste management services.

Based on the current state of the art, research studies have been dominated by investigations of the risks and negative implications of ENMs at individual end points in the SEE system, with minimal emphasis on the study of VAB (if any) for nano-based materials and products (Tolaymat et al. 2015b; Kahan et al. 2008). It is argued here that research studies are warranted to explore the positive implications and effects of ENMs within a sustainability context. Indeed, this is a critical gap in knowledge.

The primary objective of this paper is to establish an integrated framework for assessing whether or not nanomaterials and nano-enabled products contribute VAB. The study objective is accomplished via the following specific aims: (1) to investigate the determinants of VAB and its relationship to sustainability within the context of ENMs and (2) to establish a sociotechnical framework with criteria to quantify the worthiness of ENM VAB based on cost–benefit analyses, non-physical factors, socio-economic factors, and ENM contribution

to other product or process sustainability. The research questions raised in this paper are fundamental to the healthy growth of ENMs and nano-enabled products. Benefit–risk analyses are essential methods for the appraisal of nano-enabled products not only from economic standpoint but also from various perspectives including those mentioned above to advance the science of sustainable ENMs. Although the emphasis in this paper is on the sustainability of ENMs, it is believed that the concepts discussed herein are also applicable to other emerging technologies, materials, and chemicals. However, the application of the suggested sociotechnical system principles may require customization within and among the emerging technologies.

Determinants of VAB and its relationship to sustainability

Background

According to Giampietro (1994), discrepancy is inevitable when assessing the same phenomenon from different perspectives. As the larger SEE system has several constituents, it is anticipated that there may exist conflicting opinions about the ENM implications. This is a major characteristic of ‘wicked’ problems that deal with complex and ill-defined problems having roots in social complexity and extending their impact on the technical element of any sociotechnical system. Therefore, the goal here is not to maximize all values and needs. Rather, it is founded on strategic satisficing (Parrish 2010) that operates on the logic of satisfaction being achieved via the attainment of certain thresholds for multiple outcomes as opposed to constantly striving for one single prioritized outcome.

As one attempts to build a framework for value and need harmonization among the different stakeholders who are responsible for the production and regulation of ENMs in the SEE system, one needs to understand the nature of the problem and the solution characteristics of wicked issues pioneered by the seminal work of Rittle and Weber (1973). As illustrated in Table 1, there are two perspectives from social and business standpoints. Rittle and Weber (1973) provided, from a social viewpoint, guidelines for describing the nature of the problem as well as the characteristics of solutions to the problem. Roberts (2000) attributed primarily the nature of wicked issues to a high level of conflict among the different stakeholders and offered three types of strategies to deal with the situation, namely authoritative, competitive, and collaborative. The business perspective is built upon the social viewpoint by calling for the adoption of a holistic approach requiring the recognition of value identity, application of flexible methodologies mixed with rigor, a focus on the action, and continuous improvement (Australian Public Service Commission 2007; Camillus 2008; Headwaters Group 2009; Hall and Martin 2005; Vandenvroeck 2012).

The aforementioned social complexity and holistic approach dictate a system-based view to harmonize the values among the different stakeholders. Fundamentally, two essential functions exist in a system-based architecture that must be accounted for and include production and marketing as well as the regulation of risks of ENMs. This viewpoint is supported by the work of O’Connor (2006) who proposed a tetrahedral structure consisting of (a) system regulation via political organization, (b) economic organization, (c) natural systems organization, and (d) social organization. He also suggested that (a) the economic, social, and environment entities influence each other via two-way relationships and (b)

system regulation is established via one-way interaction to the other entities. Because of the wicked issues dealt with in ENMs, it is suggested in this paper that the two-way relationships should be established among all entities (including the regulatory component) to augment the value harmonization among the SEE constituents (Fig. 1).

Starting with the end in mind, all entities should be connected to benefit and risk outcomes, a representation of the positive and negative implications in the SEE system, and a barometer for the sustainability of all system elements. At the same time, all entities are connected with each other via two-way relations. The latter set of links will be instrumental in building the communication channels among all parties and provide avenues to improve human actions, hence indirectly influencing the links to the benefit and risk outcomes. Intrinsically, one should document, for each entity, the survival (e.g., economic self-sufficiency for producers) and purposeful (e.g., pioneering position of producers in society) values and their interactions. Within this context, survival values are a must for physical existence and purposeful values are essential for meaningful experiences. A clear articulation of these values becomes a necessity to the global concordance and harmonization of human actions in the sociotechnical complex adaptive systems.

To sum up, it becomes apparent that there are three sets of relationships in the SEE complex adaptive system:

- direct influence exerted by each entity on the positive and negative outcomes in the larger system—this link is applicable for all entities in the system-of-systems;
- relationships among the entities influencing the communication and human actions with subsequent impact on the benefit and risk outcomes via the direct links between entities and outcomes; and
- intrinsic survival and purposeful value interactions, being the root causes of potential wickedness impacting both the direct and indirect relationships.

These three sets of relationships are a reflection of the dynamic model (with feed-forward and feedback loops) presented in Fig. 2 (explained in the next section). It is assumed herein that different entities are governed by social agents who either have the choice to act on their own (e.g., producers, consumers) or on behalf of other living entities (e.g., environmental compartments, non-human biological entities). It is further assumed that each social agent possesses a number of resources including mental (i.e., hidden and invisible), physical (e.g., visible and nature of the human body), and social (other social agents), a generalization of Descartes' mind–body framework (Sperry 1980; Shilling and Mellor 1996). Mental health resources are mapped out to the intrinsic survival and purposeful values and their interactions. For a given entity, physical health resources are the resultant of actions induced by the body in response to the feed-forward stimuli from mental health resources and feedback stimuli via social health resources derived from other entities. Social health resources derived from other entities are also impacted by feed-forward stimuli from physical health resources. At the same time, the actions taken by other entities will influence mental health resources via feedback loops.

Determinants of VAB

The environment exists to serve the needs of all biological entities that live in it. Yet, human agents and institutions, a part of the whole, govern this environment and all biological entities via their actions. Consequently, one should determine whether or not these actions are beneficial or harmful to all entities, in other words, in both positive and/or negative means. That is, the design of ENMs and nano-enabled products, banking on its physical–chemical properties, may possess benefits to some or all SEE constituents and cause harm to some or all constituents.

The above argument echoes the perspectives of other researchers in that “it is not human technology so much as patterns of human activity that are challenging the sustainability of human development” (Parrish 2007). This suggests that benefit–risk assessment of ENMs cannot be simply conducted by the classic economic appraisal methods such as benefit–cost analyses. Therefore, a comprehensive system analysis is warranted to advance a better understanding of benefits generated by ENMs in addition to those demonstrated via economic outcomes. This is explored in the remainder of this section with emphasis on values and what constitutes VAB.

On fundamental grounds, it has been argued that relations are beneficial when they contribute positively to the existence of a given system and are therefore of value, and are detrimental when they impact a system in negative terms and are of disvalue (Parrish 2007). Therefore, a system’s existence stems from these functional value relations. It therefore appears that sustainable outcomes must relate to both value and disvalue at the same time. This relationship should be founded on simultaneously enhancing and augmenting the value and minimizing the disvalue. It should be noted that either value enhancement or disvalue minimization is a necessary condition to attain sustainability but not sufficient on its own to establish sustainable outcomes.

Because a system-based ENM architecture consists of several stakeholders, there is the possibility for varying goals and values among the different constituents. In other words, values are not absolute and are rather relative because they originate from different needs within and between stakeholders. According to Maslow’s theory (1943), there are two levels of needs at the biological entity level, namely basic needs for survivability and higher needs for purposefulness. Therefore, sustainable benefit outcomes must account for the hierarchical needs within and among biological species. Consequently, two design principles emerge that should be accounted for in the sustainable design of the larger SEE system to truly contribute VAB for the production, distribution, and use of ENMs and nano-enabled products (Parrish 2007): (a) the value of system activities must concord among the hierarchical levels (i.e., within and among the biological species and natural environments), and (b) system activities must concord for achieving integrated survival and purposeful values. It is hypothesized that these social design principles are essential inputs to the economic assessment of SEE system activities, building the ground work for a modular assessment framework as discussed in the next section.

Figure 1 shows a snapshot of the stakeholders populating the three functional interactive systems of the SEE system-of-systems. A detailed view of the supply chain's needs embedded in the stakeholders of the SEE system can be constructed in a matrix format together with the potential relationships among them (Table 2). Each element in the system is required to satisfy its survival and purposeful needs (intrinsic values represented on the diagonal cells of the matrix) as well as the needs of others (extrinsic values represented in the non-diagonal cells) in order for the whole system to survive and thrive. These needs should be satisfied within the context of value and disvalue outcomes. As such, one realizes the complexity of continually creating harmony among stakeholders with hierarchical needs and goals framed in benefit and risk outcomes.

Classically, value has been attached to material economic outcomes in the business environment (Porter and Kramer 2011). Yet, values are intangibles that are intrinsic to the human agent and are closely related to the needs and wants of social agents (i.e., humans). Therefore, as pointed out earlier, social value should be the first element considered in a framework established to examine VAB, followed by economic and technical values, respectively. That is, value ought to contribute first to society, followed by economic value in support of human values, which then drives technological values.

In general, human values function both as constraints and stimuli. Stated differently, values may operate as blockers or enhancers. In some situations, it is also possible to find “value” in a state of indifference where the states of “blocker” and “enhancer” are in balance with each other. The above view is in agreement with Rokeach (1973) who defined value as “an enduring belief that a specific mode of conduct or end-state of existence is personally or socially preferable to an opposite or converse mode of conduct or end-state of existence.” Associating value with an enduring belief suggests that values have their roots in the biological entity's mental resources. Therefore, one must understand the intrinsic attributes of value when attached to benefits.

Figure 2 shows a simple mental–physical–social resource model for human agents. According to the model, mental health resources influence physical health then social health resources in feed-forward fashion. In turn, physical and social health resources exert their influences as shown in feedback terms. The model can also be represented in terms of two layers: physical or outer (i.e., visible in terms of human body or physical health resources and social health resources or for example family and friends), and non-physical or inner (i.e., hidden such as mental health resources). In general, we know much about the physical and social health resources; yet, we have a limited understanding of the complex interactions of non-physical influencers, many of which are less tangible. Generally speaking, a material variable such as economic value can be computed in terms of the differential between potential revenues and expenses. That is, one can establish from the front end (e.g., physical world) the gains and losses. However, complex issues leading to human actions are governed by not only physical variables but also non-physical parameters that are intrinsic to the human agent.

Let us examine, for example, the saying of “beauty is in the eye of the beholder.” This is an intrinsic attribute that is sensed in the back end (i.e., mental resources) and drives the human

action of purchasing a car as long as it passes the next criterion on economic grounds. Suppose that a consumer likes the look of a car driven by another person. Consequently, he/she searches online for the same car, then discovers that it is outside the reach on economic grounds. This sends a feedback signal for the person to start another search until the intrinsic value is met and compatible with the economic value. Then, the technical specification values are evaluated sending feedback signals to the social agent and the economic criteria. The process continues until compatibility is achieved in this dynamic process.

To gain a better understanding of the internal drivers influencing human actions, one can model these effects in terms of cognitive enhancer or blocker *and* emotional enhancer or blocker that reflects human behavior resulting from the interaction between the inner and outer layers and physiological functioning throughput (Tolaymat et al. 2015a, b). A discussion of these phenomena is given below.

- a. The phenomenon of non-physical enhancer (NPE), in which the good (i.e., cognitive and/or emotional enhancer) of the internal milieu outweighs the ill (i.e., cognitive and/or emotional blocker), is an integral building block for developing sustainable ENMs and takes into account the perspective of other stakeholders. In other words, NPE is the fuel of adaptive property of living species. Therefore, a value-added benefit is a direct interpretation of an NPE outcome and can be formulated in tangible terms via the use of “Doing Good Is Good Business” as a sustainability axiom. This axiom embodies a complex meaning and several corollaries can be derived from it.
- b. The phenomenon of non-physical blocker (NPB), in which the ill of the internal milieu exceeds the good, is a primary determinant of unsustainable ENMs in which the perspectives of other stakeholders in the SEE system may not be considered or may be conflicting. NPB is thus a driver of the maladaptive property for living entities.
- c. Collectively, NPE and NPB are natural phenomena supported by empirical work in the published literature. The “broaden-and-built” theory of positive emotions as a matter of example supports these phenomena as follows: positive emotions broaden an individual’s instantaneous thought–action reservoir (e.g., interest sparks the urge to explore); by broadening an individual’s thought–action reservoir, positive emotions promote discovery of novel and creative actions, which in turn build the individual’s personal resources ranging from physical and intellectual to social and psychological resources (Fredrickson 2001). According to the theory, broadened mindsets arising from positive emotions are contrasted with the narrowed mindsets sparked by negative emotions (i.e., specific action tendencies such as attack). In addition, enhanced personal resources function as reserves that can be drawn on sooner or later to improve the odds of successful coping and survival.
- d. A third phenomenon termed as non-physical indifferent (NPI) is a tie between NPB and NPE, that is, the good of internal milieu is in balance with the ill component. This phenomenon has been widely used in economic theories in

which one starts a certain theory with no pre-conceived state, that is, indifferent in terms of the state dealt with.

It should be noted that the NPE, NPB, and NPI phenomena are directly influencing the behavior and actions of social agents ultimately resulting in ENM benefits and risks. Therefore, for ENM to be sustainable across the SEE lifecycle trajectory, mental resources should be directed towards higher and diminished states of NPE and NPB, respectively, together with a balanced state of NPI not impeding the harmonization of values among multiple stakeholders. For example, venture capitalists in a start-up company put extreme pressure on its nano-scientists and engineers to quickly design and manufacture ENM materials and nano-enabled products. This pressure produced from venture capitalists acts as feedback loops (see Fig. 2) to the mental resources of nano-scientists and engineers. This tends to narrow the perspective of scientists and engineers leading to system behavior and actions, with a focus on fewer stakeholders in the SEE system such as emphasizing human needs upon the expense of other biological species (e.g., nanomaterials may prove to be detrimental to other species along the particle trajectory). As a result, the perspectives of other constituents are not taken into account. This indicates that a broad and integrated view is required whenever a product is manufactured for human use, with an eye on the implications of such a product along the SEE trajectory.

In light of the above, all stakeholders along the supply chain or the SEE system shown in Fig. 1 should be trained and educated in this holistic approach. For example, the constituents of the producer supply chain holding the responsibility for the creation and distribution of ENMs should be trained in producing nanomaterials with VAB and negligible or zero disvalue-added risks (including those contained and controlled) using green chemistry and engineering practices. Furthermore, the role of regulation should be transformed from not only the regulation of risks but also the promotion of VAB along the SEE lifecycle trajectory. In this respect, the goal of training and education is to augment the cognitive/emotional enhancers and to diminish the cognitive/emotional blockers, with the aim to harmonize human actions and associated decisions.

In summary, there is a role for social enterprises such as training and educational institutions to facilitate the transformation for all stakeholders into the holistic paradigm espoused in Fig. 1.

Framework for sustainable ENMs

Modular approach for sustainable ENMs

The development of raw ENMs and nano-enabled products by scientists and product engineers assumes that the novelty and innovation of these gadgets originate in their unique physical–chemical properties, being deployed in applications which lead to social and economic benefits to a faction of SEE constituents. A historical account of prior materials such as asbestos suggests that a narrow perspective of the VAB from the producer viewpoint may eventually be disastrous financially, socially, and ecologically (Sanchez et al. 2009). Therefore, a broader perspective must be considered within the context of value- and disvalue-added activities and sustainable outcomes for stakeholders involved in ENM

production, use, and related matters. Taken together, one needs to augment benefits and reduce risks to attain the ultimate goals of sustainable ENMs, while taking into account the lifetime expectancy for a given product. This means that a sustainable product is not indefinite and has a longevity requirement.

As such, sustainable ENMs are defined in this paper as chemicals contributing VAB and producing negligible or no harm (including those contained and controlled) to the SEE during product use over a life expectancy defined for the material at hand. A material in its lifetime may pose minimal disvalue, but the use of that material to fulfill human needs until society evolves may actually introduce unsustainable consequences. Therefore, this definition carries into it the attributes (i.e., VAB and minimal risks) and the boundaries of sustainable ENMs. Any disturbance in the inputs exemplified in the sociotechnical parameters or the output in terms of the needs of SEE constituents will push it towards the boundaries of unsustainable ENMs.

Both benefits and risks are ingrained not only in the ENM physical–chemical properties, but also in the human actions that lead to the design of ENM raw materials and products as well as their use. Therefore, we need to adopt a sociotechnical methodology (STM) (Cherns 1976, 1987) that binds the social institution with the industrial technological enterprise to produce the design properties of sustainable ENMs in a coherent way. The STM principles are based on human logic, common sense, and the experiences accumulated over the years. However, they need to be developed and customized for the use of sustainable ENMs. For demonstration purposes, two principles are discussed and interpreted within the context of sustainable ENMs.

- ‘Compatibility’ is required between the design process and its objectives. That is, one has to design sustainable ENMs to contribute VAB and to achieve risk minimization to the SEE constituents. Therefore, it is imperative that the ENM implications must be examined and acted upon at the pre-design as well as the design stages. In this respect, the role of regulatory agencies can be transformed from not only the reduction and elimination of risk, but also, the enrichment of product VAB.
- The compatibility axioms are hinged upon a cross-functional team to produce the intended results as discussed in the previous section (e.g., material scientist, manufacturing engineer, venture capitalist, cognitive scientist, toxicologist, environmental scientist, internal regulatory subject matter expert, government affairs) and in line with the ‘multifunctional’ principle. Because the cross-sectional team consists of several agents, it is expected that each agent brings different ideas to the table; therefore, the complex objectives can be accomplished from a broader perspective and can take into account the different endpoints for value creation and disvalue minimization/elimination.
- ‘Support congruence’ implies the critical role of support systems in producing sustainable ENMs. Naturally, it should be equally shared between the regulatory and producer entities responsible for the production and control of ENM benefits and risks. That is, the relationship between producers and regulators should be

built on the basis of a shared understanding designed to harmonize the quality of life for all SEE constituents including the producers. Currently, there is a push by OECD (2012) to advance the role of producer responsibility in a sustainable economy.

One should remember that the principles of green chemistry and engineering, as technical factors, supplement the role of the above-mentioned social parameters. Therefore, a modular approach is essential to connect the social and technological design principles leading to truly sustainable ENMs. The social principles should be first implemented at the pre-design stage of nano-based products, then the green chemistry principles at the design stage of products.

Integrated framework

The framework would serve as a vehicle for all stakeholders to understand the whole and its parts with regard to the benefits of ENMs in the large SEE system and what constitutes sustainable ENMs. It is expected that the use of an architecture such as the one depicted in Fig. 1 would be a communication vehicle to provide a platform to integrate many system analysis tools such as life cycle assessment and multi-criteria decision analysis (Tolaymat et al. 2015a) to examine the full scope of ENM benefits for all constituents. In essence, the system is built upon the foundational aspects of sustainable nanomaterials. First, the VAB test should be demonstrated at the pre-design stage of ENMs. In this respect, the social principles of design should be instituted and reviewed to ensure that the needs of all stakeholders in the SEE system are met at the pre-design stage. Once satisfied, the second step is to ensure at the design stage that ENMs should pose no greater than minimal levels of risk to the SEE constituents. Minimal levels of risk can be based on synthesized knowledge from the scientific literature for nano-products as well as cumulative experience built from “what we know” from other products over the years (Tolaymat et al. 2015b). A third step would be devoted towards accounting for the iterative evaluation in the STM principles. This process should be integrated with the classic economic benefit–risk assessment to cover all elements of valuation.

Figure 3 illustrates the four fundamental steps of the sociotechnical framework. The first step involves SEE stakeholder training and education. This step must start with a global understanding of the whole and its parts as displayed in Fig. 1. This should include a grasp of the different types of interrelationships influencing the benefit and risk outcomes and the sociotechnical principles powering the production of sustainable ENMs and nano-based products. Then, at the pre-design stage the VAB of the intended ENMs and nano-enabled products should be established prior to the development and production of commercial raw ENMs and nano-enabled products. This is a mandatory step and the first line of defense to protect the SEE constituents. It is advocated that regulation should have a role at the pre-design stage by being concerned with not only the control of the risks of negative implications but also the establishment of positive implications as well.

The pre-design stage would consist of two sequential elements connected in a feed-forward fashion and assessed from a social–ecological perspective with respect to its constituents,

followed by the classic economic benefit–cost analyses. For the suggested social–ecological evaluation, one ought to create a sustainability function that takes into account the unique physical–chemical properties of ENMs in contributing benefits and harm to the different segments of society, environment, and economy. This function can be formulated on the basis of an expert panel consisting of subject matter experts representing the different stakeholders. Collectively, to add value, benefits should be pointing to the direction where the biological entity in question or the natural environment can successfully adapt or function on survival and purposeful grounds in the larger SEE system. Additionally, disvalue in the evaluation should not be pointing to a direction where the biological entity or the natural environment is in a state of maladaptation due to the feedback stimuli. The time boundaries should also be examined to ensure the completion of sustainable outcomes. In addition to the above, the social elements of the sociotechnical design principles should be detailed to bring compatibility to the needs and wants of the SEE stakeholders.

If the VAB assessment passes the criteria decided upon, the design stage can then be instituted benefiting from the principles of green chemistry for the purpose of reducing the harm (if any) to minimal levels among constituents of the SEE system. In essence, the strategies of green chemistry include “the utilization of a set of principles that reduces or eliminates the use or generation of hazardous substances in the design, manufacture, and application of chemical products” (Anastas and Warner 1998). Since nanotechnology is still in the developmental stage, producers should seize this opportunity to adopt green manufacturing practices to minimize the hazards. To achieve this goal, the U.S. Environmental Protection Agency (U.S. EPA) outlined green chemistry principles and mapped them out into action via green engineering principles (Schmidt 2007). These principles and practices are universal and applicable to any technology intended to commit to green manufacturing so as to minimize or eliminate the technology’s negative environmental and health impacts. It should be noted, however, that these principles need customization to suit the needs of the technology at hand. For example, a principle calling for degradation after use is not applicable to all classes of ENMs. Metal and metal oxide ENMs are not degradable. Thus, they will accumulate in the environment after use. This accumulation does not necessarily imply that ENMs will be harmful to the environment. Silver nanoparticles are inherently toxic but the presence of AgNPs in the sludge (a byproduct of wastewater treatment processes) can result in the sulfidation of AgNPs, rendering them inert materials and consequently, not harmful to the environment (Levard et al. 2010, 2013; Li et al. 2013).

The iterative step in the process will re-examine the sociotechnical elements of design to ensure that sustainable outcomes are planned for. Additionally, due to the unique characteristics of a given ENM and the unlimited number of newly created chemicals, the process should be enacted as an adaptive cycle ready to be examined periodically, for instance, every 3–5 years.

Discussion and concluding remarks

In this research, it has been postulated that healthier societies, environments, and economies are jointly built for longevity by adopting sustainable solutions, within the context of

sociotechnical design, to fulfill the needs and wants of its diverse constituents. With this in mind, this study was conducted to explore the potential to establish an integrated sociotechnical framework, with the end goal to assess whether or not ENMs and nano-enabled products contribute VAB. Based on the research in this paper, one can make a number of observations.

- In general, a systematic review of the literature suggests that very little research has been performed with respect to the VAB for ENMs. This observation is in agreement with the views of Wiek et al. (2013) who stated that nanotechnology is often touted as an important contributor to sustainability without scrutinizing its benefits to the solution space. Within this context, a system-based view such as that in Fig. 1 with much greater details is required in order to understand the multiple interrelationships within and between the stakeholders of the SEE making up the space of the ENM particle lifecycle trajectory.
- The conditions and boundaries of sustainable ENMs have been defined. Therefore, it is believed that, on sustainable grounds, ENMs should strive to contribute VAB and minimal risk levels to all stakeholders in the SEE system within a certain life expectancy. This definition of sustainable nanomaterials is in agreement with the collective work of others in sustainability research. Marshall and Toffel (2005) discussed a sustainability hierarchy with several levels. In the hierarchy, the authors maintained that level 4 endeavors to build harmony with values, beliefs, or esthetic preferences. Although Marshall and Toffel (2005) argued to not include level 4 issues due to its large scope, it is maintained herein that wicked problems necessitate the optimization of all stakeholders' values in order to truly achieve sustainable development. On practical grounds, while one cannot maximize value for each constituent, it is possible to reach middle grounds to satisfy the needs of SEE constituents. Costanza and Patten (1995) maintained that life expectancy should be built into the concept of sustainability because different elements of a sustainable system have different life expectancies. The proposal introduced herein for sustainable ENMs requires proactive actions to go beyond the survival attributes of sustainability.
- Value is an intrinsic property of biological species and the natural environments. A representation was presented to discuss the need to augment the enhancers and to diminish the blockers for social agents. This is essential in order to broaden their view with an eye to enrich the VAB for all SEE constituents. Training and education would be paramount towards achieving this goal.
- At the pre-design stage of the framework, VAB should be assessed using an expert panel representing the different segments of SEE with the objective to enhance the sustainability function for all constituents. Furthermore, the social design principles of ENMs and nano-enabled products should be detailed and customized to their needs in order to bring compatibility in terms of the VAB.
- At the design stage of the framework, one needs to practice the green chemistry and engineering principles, with the goal to significantly reduce if not eliminate the potential risks of ENMs and nano-enabled products along the particle

lifecycle trajectory. This is essential to ensure the safety of synthesized ENMs once released into the environment either during manufacture, use, or disposal at end-of-life. Silver ENMs' synthesis preprocesses, for example, can be made greener through the use of plant extract (e.g., *Rumex hymenosepalus* plant extract and tea extract) as reducing and stabilizing agents (Rodríguez-León et al. 2013; Nadagouda and Varma 2008) instead of using hazardous chemicals such as sodium borohydride (Tolaymat et al. 2010). Although the synthesis method has become green and the synthesized silver can be used to make other environmental processes green [e.g., biocidal filter for water disinfection (Prashant and Pradeep 2005)], the resulting silver ENM is inherently toxic and can still pose hazards to human health and the environment once released during manufacture, use, and/or disposal at end-of-life (El Badawy et al. 2011). In order to overcome this issue, the knowledge amassed on the subject should be exploited to make the particle and material behavior green once released into the environment. As another example, El Badawy et al. (2011) reported that positively charged silver ENMs are much more toxic to bacteria as compared to negatively charged silver ENMs. Therefore, one can manufacture silver ENMs with negative charges in the absence of any need of particles with positive charges. The aforementioned examples highlight the critical need for an integrated approach at the design stage in which collaborative efforts among different stakeholders in the SEE system are sought to produce functional nanomaterials using green approaches with minimal impacts upon release into the environment. In addition, the technical component in an STM should consider integrating green chemistry and engineering principles and practices at different levels in the economy ranging from industrial systems to science and engineering curricula to public awareness. The primary message is to embed a system-of-systems thinking into the manufacturing of ENMs and nano-enabled products for sustainability purposes.

- The final step in the framework presented is an adaptive step to ensure that the knowledge accumulated while instituting the sociotechnical approach is re-examined on a periodic basis to continuously improve the process.

Future research will address the concepts and principles discussed in this paper to ENM applications such as integrated food–water–energy systems to exploit the opportunities and contain the challenges of nanotechnologies.

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Abbreviations

SEE	Society–environment–economy
VAB	Value-added benefits

ENMs	Engineered nanomaterials
NPE	Non-physical enhancer
NPB	Non-physical blocker
NPI	Non-physical indifferent
STM	Sociotechnical methodology
OECD	Organization for Economic Co-operation and Development

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Fig. 1.
Stakeholders populating the complex interactive system of society, environment, and economy

Fig. 2.
Representation of mental–physical–social model for human agents

Fig. 3.
Steps of sociotechnical framework

Table 1

Characteristics of wicked problems (WPs)

Source	Work description	Contribution
Rittle and Weber (1973)	<p>WP characteristics:</p> <ol style="list-style-type: none"> 1. No definitive formulation of WP 2. No stopping rule 3. Solutions are not true or false but good or bad 4. No immediate and no ultimate test of a solution 5. Every solution is a “one-shot operation.” Because there is no opportunity to learn by trial and error, every attempt counts significantly 6. WPs do not have an exhaustively describable set of potential solutions, nor is there a well-described set of permissible operations that may be incorporated into the plan 7. Every WP is unique 8. Every WP can be considered a symptom of another problem 9. The existence of a discrepancy representing a WP can be explained in multiple ways. The choice of explanation determines the nature of the problem’s resolution 10. The ‘problem solver’ has no right to be wrong 	<ul style="list-style-type: none"> • The authors introduced the original concept of WPs
Roberts (2000)	<ul style="list-style-type: none"> • WPs engender a high level of conflict among stakeholders. That is, there is no agreement on the problem or its solution • Three generic strategies are offered to resolve WPs (authoritative, competitive, and collaborative) • Authoritative strategies are ‘taming’ interventions to diminish the level of conflict by assigning the issue at hand into the hands of a few stakeholders who have the authority to define a problem and come with a solution • Competitive strategies assume a “zero-sum game” leading to win-lose situations • The foundation of collaborative strategies is “working together” on the premise that, by joining forces, parties can accomplish more as collective than by acting as independent agents 	<ul style="list-style-type: none"> • Roberts presented a possible set of strategic solutions to WPs • The implementation of a mixed basket of solutions may vary from problem to problem
Australian Public Service Commission (2007)	<p>Characteristics of WPs:</p> <ul style="list-style-type: none"> • Difficult to clearly define • Multi-causal interdependencies • Unforeseen consequences • Not stable • No clear solution • Socially complex • Responsibility of multiple organizations • WPs involve changing behavior • Chronic policy failure 	<ul style="list-style-type: none"> • Simplified the characteristics of WPs
Conklin (2005)	<p>Similar to the work of the Australian Government, the author developed simpler and fewer characteristics:</p> <ul style="list-style-type: none"> • You don’t understand the problem until you have developed a solution • WPs have no stopping rule (further explained as: since there is no definitive ‘problem,’ there is also no definitive ‘solution’) • Solutions to WPs are not right or wrong • Every WP is essentially unique and novel • Every solution is a ‘one-shot operation’ • WPs have no given alternative solutions 	<ul style="list-style-type: none"> • Simplified the characteristics of WPs
Camillus (2008)	<p>The author concluded based on analysis of industrial enterprises that, when five characteristics are present in a strategy-related issue, company executives confirm the presence of a WP. The five characteristics include:</p> <ul style="list-style-type: none"> • The problem involves many stakeholders with different values and priorities • The issue’s roots are complex and tangled • The problem is difficult to come to grips with and changes with every attempt to address it • The challenge has no precedent • The author offered the following guidelines to managing the wickedness of business strategies: • Involve stakeholders, document opinions, and communicate • Define the corporate identity (i.e., values, competencies, aspirations) • Focus on action • Adopt a feed-forward orientation 	<ul style="list-style-type: none"> • Presented a management approach to assess and resolve WPs in industrial enterprises
Headwaters Group (2009)	<ul style="list-style-type: none"> • In collaboration with professors in business school, a philanthropic framework was developed in an attempt to solve complex societal issues • This organizational framework calls for a move away from the classic demand and control management model to a more inclusive, collaborative, and dynamic strategic approach 	<ul style="list-style-type: none"> • Presented a modern application to the management of WPs in industrial settings

Source	Work description	Contribution
Hall and Martin (2005)	<ul style="list-style-type: none"> • The authors suggested the use of an evaluation framework for disruptive technologies that incorporates stakeholder theory, innovation management concepts, and evolutionary learning methodology of science to social issues • Stakeholders include primary (e.g., customer, investor, suppliers) and secondary (e.g., environmental activists) agents • It was argued that a trial-and-error approach can be applied to issues encountering technological, commercial, and organizational uncertainties • A case study was presented for the framework application to Monsanto's agricultural biotechnology 	<ul style="list-style-type: none"> • The authors combined a number of techniques from the scientific literature. Yet, the approach is hard to apply to practical settings
Vandenvroeck (2012)	<p>The author presented five lessons learned from dealing with WPs:</p> <ul style="list-style-type: none"> • Mix flexibility and rigor • Pursue goal-oriented incrementalism • Think abundance, not scarcity • Develop a view of the whole • Reframe wicked problems into wicked opportunities. 	<ul style="list-style-type: none"> • Similar to the work of Roberts (2000), the lessons learned presented insights into how to improve the solutions to WPs

Table 2

Intrinsic (I) and extrinsic (E) needs of SEE stakeholders

I ₁₁	E ₁₂	E ₁₃	E ₁₄	E ₁₅
E ₂₁	I ₂₂	E ₂₃	E ₂₄	E ₂₅
E ₃₁	E ₃₂	I ₃₃	E ₃₄	E ₃₅
E ₄₁	E ₄₂	E ₄₃	I ₄₄	E ₄₅
E ₅₁	E ₅₂	E ₅₃	E ₅₄	I ₅₅