TOWARDS A UNIFIED INDEX FOR ASSESSING THE SUSTAINABILITY OF WASTEWATER IRRIGATION

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ABSTRACT

Indicator-based sustainability assessments are useful tools in portraying the complex system of water reuse in agriculture in a simple manner. However, the growing number of indicator factors used has haltered comparability and ease of use of the indices. This working paper presents an indicator-based framework to support policymakers in assessing the level of sustainability of water reuse practices in agriculture on a regional and/or national level. The sustainability index consists of two sub-indices, assessing the environmental and socioeconomic dimensions, respectively. The index is designed in accordance with the steps proposed by the Organisation for Economic Co-operation and Development (OECD), namely indicator selection, normalisation, weighting, aggregation, and robustness analysis. A minimum set of indicator factors were identified based on the existing literature and are normalised according to 'distance to target'. Principal Component Analysis (PCA) is used for their weighting and further number minimisation. The overall index ranges from 0 to 1, according to the level of sustainability of the applied wastewater practices in irrigation.

Keywords: indicator, sustainability assessment, conceptual framework, wastewater, policymaking, national

1. Introduction

Water scarcity is a rising concern in many arid and semi-arid regions of the world, especially in countries where agriculture is a major economic contributor (Winpenny et al. 2010). Wastewater is a reliable alternative water source, and in the past it has been primarily used for irrigation purposes under different conditions (Hettiarachchi, Caucci, and Ardakanian 2018; UNDP 2017), providing not only volumes of water, but also the nutrients necessary for the optimal growth of crops. However, when untreated wastewater is applied, it can expose the ecosystem to socioeconomic threats. Excessive levels of nitrogen and phosphorus, and a concentration of heavy metals or pathogens in the soil, could negatively affect soil health. As a consequence, such contaminants can potentially get in contact with crops and groundwater, which subsequently results in them being introduced into the food chain (Rahman, Riesbeck, and Dupree 2018). The risk to public health and safety, as well as hampered economic activities, should be avoided at any cost; thus, preventive measures are critical when applying wastewater irrigation in agriculture.

Effective and targeted policies can sustainably promote water reuse through the development of regulatory frameworks and tools that could support the decision-making processes. However, policy design often fails to take sustainability criteria into consideration (Metz and Ingold 2014). Until recently, the relevance of science-policy interface research has not been adequately addressed or elaborated upon and has lagged behind more traditional studies, which have focused on water reuse from a siloed resource perspective. The recent changes to resource research approaches have begun to invert this trend, and with steady progress, wastewater irrigation policies can move toward a more sustainable solution in many regions of the world (Vlachogianni et al. 2018; Dunn, Bos, and Brown 2018; López-Rodríguez et al. 2015).

The system dynamics of wastewater application in agriculture (irrigation) have multi-layered factors, which impacts the boundary system on environmental, social, and economic dimensions (Hettiarachchi, Caucci, and Ardakanian 2018). However, the measurement of such impacts is not straightforward, and monitoring strategies capable of capturing the system changes are often required in the designing of sustainable policies.

Sustainability lies at the very foundations of the Sustainable Development Goals (SDGs) set by the UN in 2015 (Griggs et al. 2017), and in order to achieve these SDG targets, monitoring strategies and tools have been developed as instruments for adopting and measuring sustainable policies.

A prominent tool for SDGs monitoring is that of sustainability assessment, which can aid in the comprehensive translation of complex socio-economic-environmental interactions into policies (Weaver and Rotmans 2006). Furthermore, sustainability assessments can be used in decision-making processes, where the analysis of environmental systems should be posed alongside both social and economic components.

Although the tripartite sustainability exercise has been implemented in multiple systems, the role of sustainability assessment in wastewater irrigation has been mostly addressed in terms of its environmental dimension, while largely underestimating the role of socioeconomic actions. Moreover, for the few cases in which sustainability assessments in wastewater irrigation has shown tri-dimensionality, studies have often failed to simplify the outcomes, thus reducing their impact on policymaking processes.

The complexity of these outcomes for sustainability assessments for wastewater irrigation in agriculture can be attributed to the abundance and diversity of indicators used for the evaluation of the practice, resulting in the comparability of the study becoming difficult, with little appeal in reproduction.

With this work, we aim at synthesising an index that ultimately supports policymakers in assessing both the level of sustainability of wastewater application in irrigation practices and the implementation field on which intervention should focus when improved sustainability of the practice is needed. An indicator-based framework will be used for the sustainability assessment. The boundaries defined in this study are represented at the state and/or regional level/s.

No new indicators are to be generated by this study, rather, the main aim of the working paper is to optimise the process of knowledge already gained from research and real case application of wastewater irrigation practices. To that end, a minimum set of appropriate indicators is identified, thus enhancing the effectiveness of indicator-based sustainability assessment applicability.

2. Background Information

2.1 A Categorisation of Sustainability Assessments

Many frameworks and tools have been developed over the years to assess sustainable practices. These can be categorised into indicator-based, product-related and integrated sustainability assessment methods (Ness et al. 2007). The different categories are presented in Table 1.

Indicator-based frameworks can describe a specific feature or sustainability dimension via the selection of an indicator. These indicators are either integrated into an index, by aggregating different dimensions of sustainability or used separately with the intention of highlighting a specific aspect or dimension of sustainability (Singh et al. 2012; Ness et al. 2007).

Over the years, the trend of addressing siloed information on a specific dimension of sustainability has generated many complex indicators with varying limitations in information transference, which has subsequently led to hindering the implementation of indicator-based frameworks on a large scale. As the current research tendency leads towards a holistic approach for a systems understanding of natural resource management, a change in the perception of sustainability has been noticeable. As a result, sustainability assessments have moved away from

the reductionistic approach of siloes understanding (Bond and Morrison-Saunders 2011; Gasparatos and Scolobig 2012) to make way for newly integrated indices with an increasing demand for real-life applications. Indicative examples include the Wellbeing Index (Prescott-Allen and Resources 2001) and the Environmental Performance Index (Wendling et al. 2018).

Indicators can indeed better highlight the social dimension, according to the growing literature (Michaela Saisana and Tarantola 2002; Zhou et al. 2012; Ness et al. 2007).

Table 1: Sustainability assessment categories (Source: Ness et al., 2007)

Category	Description	Examples
Indicator-Based	Use indicators to describe a specific aspect of a system or sustainability dimension. These indicators are either integrated into an index or used separately.	Environmental Performance Index, SEAMLESS-IF
Product-Related	Often used in industry for the assessment of production and/or consumption of goods and services. They consider material flows and energy use at each step of the production and consumption process.	Life Cycle Assessment, Life Cycle Costing, Product Energy Analysis
Integrated	Mostly used in project or policy decision-making actions. They look at the understanding of a system as a whole, through alternative scenarios and conceptual modelling. They combine a variety of methodologies and tools.	Multi-Criteria Analysis, Vulnerability Analysis, Risk Analysis, Cost-Benefit Analysis

2.2 Indicator-based Sustainability Assessment: Why a Composite Index?

The selection of which methodology to be applied in a sustainability assessment depends mostly on the scope of the assessment itself (Ness et al. 2007). The proposed framework aims at supporting policymakers; the ease and simplicity of the assessment are the principal conditions for the selection of the sustainability assessment method.

Policy implementation for water reuse has recently been a subject of much attention in Europe. The European Union (EU) allocates most of its treated wastewater for agricultural irrigation. As such, steps towards a regulatory framework are ongoing (EC 2016). In this context, integrated indicator-based assessments can effectively

contribute to developing and enhancing the already existing regulatory framework (Alcalde-Sanz and Gawlik 2017). These indicators can define the efficiency of water reuse, highlight gaps in the regulatory framework, and outline areas in which regulatory frameworks have not been applied.

Current indicator-based sustainability assessments lack in providing a holistic view of wastewater practices in agriculture and subsequently fail to communicate effective and meaningful results to policymakers. As a prerequisite of this study, the assessment method selected must represent all dimensions of sustainability, and the assessment results will be communicated in a simple and effective manner. Overrepresentation of environmental indicators in the sustainability assessment of wastewater irrigation in agriculture should be avoided, and the weighting of the factors is considered of relevance in such context. Such requirements can be met only with indicator-based frameworks and specifically, with the adoption of a composite (or integrated) index.

Another reason for the adoption of the integrated indicator-based frameworks (I-IBF) lies in the ability of the method to combine the assessment of multiple dimensions into a single index. Although indicators do not provide a dynamic representation of systems, when frequently measured, indicators can inform policymakers on the effectiveness of policy implementation measures (Mayer 2008).

Known indicator-based sustainability assessments for wastewater irrigation in agriculture are frequently defined at the micro or farm level, which neglects the potential for presenting the status of sustainability at the catchment and national level, which is particularly relevant for policymakers. It is for this reason that the scope for the assessment encapsulates water reuse practices in agriculture at a national or regional level. The proposed index is to be used in existing cases of wastewater irrigation and applied to ex-post evaluations, i.e. in cases where wastewater irrigation practises for agricultural landscapes are already in use.

3. Developing the Framework

3.1 An Overview of the Sustainability Index

It is imperative when shaping a framework targeting policymakers, that the selection and combination of the indicator factors are undertaken in an efficient and simple manner. Therefore, indicator factors that define the integrated indicator must be comprehensible by the stakeholders that have been called upon to provide the status of an existing wastewater practice. If correctly designed, the relevant impact on the environmental and socioeconomic dimensions is easily identifiable, and policymakers can refer to this information in their decision-making process.

Figure 1 illustrates the structure of the proposed index. Indicator factors are aggregated to form indicators, which in turn form the two proposed sub-indices. These sub-indices are then aggregated to form the overall Sustainability Index (SI). An indicator factor is the individual measurement that partly explains an indicator. The combination of the appropriate indicator factors will provide the information for the indicator.

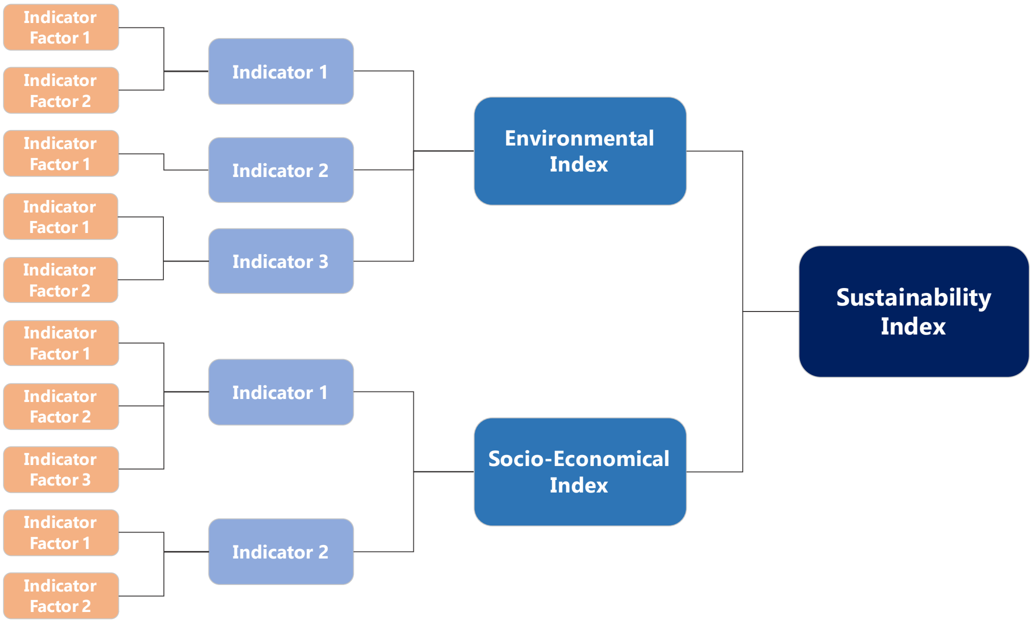

Figure 1: Structure of the Sustainability Index (SI) for assessing wastewater use in agriculture.

The overall index ranges from 0 to 1, with 1 being the most sustainable scenario of wastewater practice and suggests the total sustainability of the current practice of water reuse for irrigation. The two sub-indices (Environmental Index and Socioeconomic Index) assess the sustainability in both the environmental and socioeconomic spheres of sustainability. The indicators should provide insight on a broader scale, with wide-ranging information on the specific impact of wastewater application in agriculture.

3.2 Methodological Reasoning of the Sustainability Index

Identifying the targeted characteristics of dimensions is a challenging but essential step; special attention must be given to the proper selection of the indicator factors and methodological approaches.

Figure 2 outlines the methodological structure of the SI. According to OECD, the steps that enable the creation of a composite indicator are a) the selection of the indicators and indicator factors, b) the normalisation, weighting and aggregation of the factors and c) the robustness analysis (Nardo et al. 2008). Here, we followed this methodological process:

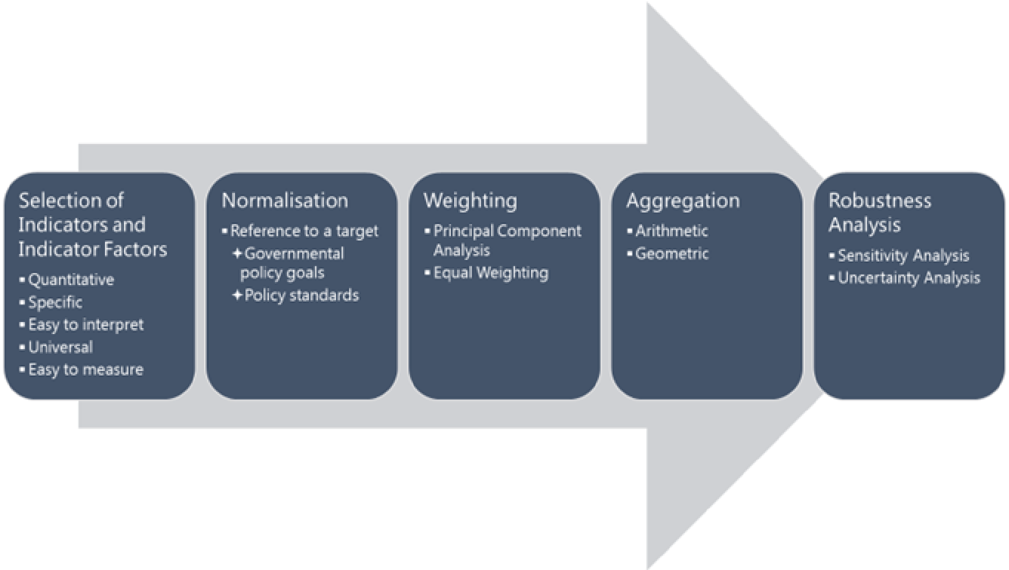

Figure 2: Steps for creating the Sustainability Index.

3.3 Selection of the Indicators and Indicator Factors

3.3.1 Indicators

The first step in developing the sustainability index is defining the impacts to be assessed, which translates to determining the appropriate indicators for the index. Both indicators and indicator factors must be widely accepted and recognised for their suitability. The appropriate indicators form the two sub-indices, which are the environmental (ENI) and the socioeconomic sub-index (SEI), each assessing the respective dimensions.

3.3.1.1 Environmental Index

Four indicators are used for the Environmental Index: assessing the status of the quality of wastewater, soil, surface water and groundwater (Figure 3). The Environmental Index ranges from 0 to 1, with 1 being the optimal state, where all indicator factors meet the policy standards, and 0 being the most unsustainable practice. Each indicator gives the state of the physical component it assesses with respect to the impacts caused by the wastewater application. The selection of these indicators has been made based on literary reviews, and as such, each indicator has been proven to be highly relevant to wastewater applications in agriculture.

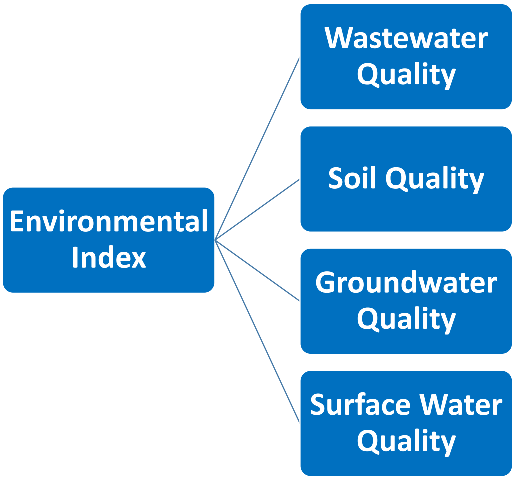

Figure 3: Environmental Index of the Sustainability Index and its respective indicators.

Wastewater, specifically, is the source of contamination for the agricultural system of study and therefore, its quality is of great significance. The type of wastewater to be assessed could include industrial, municipal, or a mixture of the two based on the source of generation, each having different characteristics in the concentration of the contaminants it carries. Furthermore, the concentration of these contaminants differs according to the level of treatment the wastewater has undergone. Consequently, the level of treatment is taken into consideration for this framework.

The second indicator is soil quality. Soil is usually the first recipient of wastewater discharge, and therefore the area where impacts are most prominent. Soil quality is important not only for the quantity of agricultural production but also because it absorbs the contaminants and pathogens that are harmful to humans, which are absorbed to some degree by the crops that are irrigated.

Groundwater is another recipient of wastewater which, when discharged, is an effective way of aquifer recharging. However, contaminants then leach through the soil into the groundwater horizon and are subsequently transferred to the aquifer, affecting its quality. With the exception of pathogens, heavy metals and organic contaminants, which could affect human health, excessive phosphorus and nitrogen that is found in the wastewater can cause eutrophication.

Wastewater can also affect the surface water quality upon its discharge into a larger body of water before it is used for agriculture. Still, the inclusion of this indicator is case-specific; wastewater is directly discharged into the soil as in many regions. When wastewater is directly discharged into a river, its quality is greatly affected and is, therefore, an essential indicator that cannot be entirely omitted.

3.3.1.2 Socioeconomic Index

The SEI also ranges from 0 to 1, in the same way as with the Environmental Index. The social and economic dimensions are assessed in an integrated manner, as the distinction between the two is arbitrary and unclear (Moldan, Janoušková, and Hák 2012). Impacts related to the well-being of the people and the economy are also referred to: the three indicators being Equity, Wastewater Treatment Cost and Income of Farmers (Figure 4). The SEI, as with the Environmental Index, aims to isolate the factors affected by wastewater application only. Therefore, each indicator is represented by those factors alone.

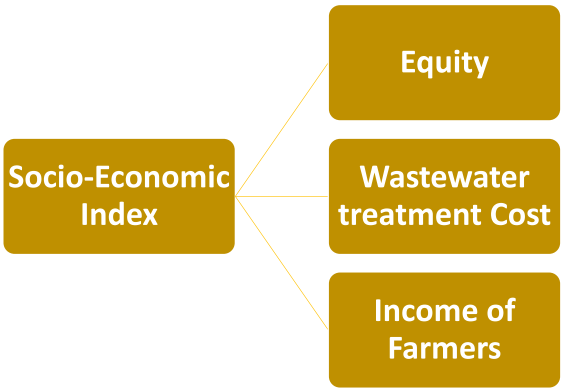

Figure 4: Socioeconomic Index of the Sustainability Index and its respective indicators.

The Equity indicator assesses impacts from wastewater that could influence the equal status of the people in the society. This translates into equal opportunities and benefits for both the farmers and the residents of the municipality/community surrounding the agricultural area (Fleurbaey et al., 2014), in areas including the health status of the people, working hours, the percentage of the people working in the agricultural sector, as well as the overall State income that is derived from agriculture.

A farmer's income is mainly comprised of economic indicator factors which affect the profitability of farming. The investment cost of the wastewater treatment is considered a separate indicator, as the main groups that are impacted are the municipality and/or the government. The Wastewater Treatment Cost is also a conditional indicator, as wastewater is often applied without any treatment.

The SEI can be used to have a static view of the socioeconomic impacts, as well as giving an overview of the additional costs or benefits that stem from the wastewater practices.

3.3.2 Indicator Factors

An initial set of indicator factors intended to measure a specific aspect of the impacts from wastewater use in agriculture has been selected; the importance of an appropriate set of indicator factors lies in the message conveyed by the indicators and indices (Niemeijer and de Groot 2008). Different sets of indicator factors will provide different information about the scope that is assessed, and conclusions may alter as a result. After the initial set of factors is selected, they will be reduced to those that are deemed the most suitable, based on statistical and participatory techniques.

According to the selection criteria of this framework, the indicator factors should be quantitative while targeting the measurement of the impacts of wastewater use in agriculture; easy to interpret and universal in their applicability, as well as not being bound to the specific characteristics of a region. Furthermore, as one of the main challenges in sustainability assessments is data availability, the proposed set of indicator factors must be easily measurable or obtainable.

Appropriate indicator factors have been utilised and tested in many previous assessments focused on water reuse in irrigation, and as such, the selection of the dataset is based on the available pool of indicator factors. Indicator factors must be both scientifically sound and generally accepted by the scientific community, stakeholders and policymakers (Hak, Kovanda, and Weinzettel 2012). Therefore, the proposed dataset will primarily be founded on the existing scientific literature, before being re-evaluated based on scientific and public judgement.

3.3.2.1 Environmental Indicator Factors

An initial set of indicator factors is selected for the measurement of the quality of wastewater, surface water (when applicable), groundwater and soil. As previously detailed, these factors have been selected from the pool of pre-tested and scientifically acknowledged indicator factors, with each indicator factor being allocated a category in accordance with its nature, i.e. the type of information they provide - for example, indicator factors measuring Electric Conductivity or pH are allocated to the Chemo-physical category.

Table 2: Categorisation of environmental indicators and indicator factors

Indicators	Categories of Indicator Factors
Wastewater Quality	Heavy Metal
	Chemo-physical
	Microbial
Surface Water Quality	Heavy Metal
	Chemo-physical
	Microbial
Soil Quality	Heavy Metal
	Soil Nutrient
	Biodiversity
Groundwater Quality	Heavy Metal
	Chemo-physical
	Microbial

3.3.2.2 Socioeconomic Indicator Factors

The selection of indicator factors for the SEI was made with the intention of describing the complex system of the socioeconomic spheres of sustainability. Given the high interconnectedness of the two dimensions, these factors were selected to assess the overall well-being of the people/community, as well as the financial costs/revenues of wastewater application.

Table 3: Categorisation of socioeconomic indicators and indicator factors

Indicators	Indicator Factors
Equity	Days of hospitalization
	Health inequality ratio
	Working hours
	Labour force
	Income from agriculture
Wastewater treatment cost	Wastewater treatment cost
Income of farmers	Price of crops
	Productivity
	Cost of fertilizer
	Cost of freshwater
	Taxes/Price of wastewater

3.4 Normalisation

The normalisation process follows the selection of the indicator factors, whereupon they are transformed into unitless values. As the factors are expressed in different units, they are not comparable and therefore cannot be aggregated. There are several normalisation methods, each appropriate for different cases (Gaidajis and Angelakoglou 2016; Nardo et al. 2008; Pinar et al. 2014; Pollesch and Dale 2016; Zhou et al. 2012). The most commonly used methodologies are summarised in Table 4.

Table 4: Most common normalisation methods

Method	Use
Reference to a target (or benchmarking)	Often used in policy-oriented indicators or in industry performance evaluation.
Standardisation (z-score)	Better used when extreme values are not present.
Min-max approach	Most appropriate when external reference for comparison is not available or unsuited. This method uses the minimum and maximum values of the dataset as reference.

For the development of the SI on water reuse in agriculture, the method 'Reference to a target' has been chosen for its relevance, as the index is intended to support policy optimisation. Each indicator factor's observed value is compared to a reference value in order to assess its quality.

The 'Reference to a target' method provides a comparison of the observed variable (indicator factor) to a target or optimal level; this is meaningful if the comparison is generally accepted (Rickard et al. 2012). The selection of the appropriate target is critical, as it will change the meaning of the index. Proposed alternatives for standards are scientific thresholds, global standards or local standards (Mori and Christodoulou 2012).

Different functions are applied to the relationship of normalisation to the reference value, according to the properties of the factor analysed. Furthermore, if the dataset has a highly-skewed distribution, the values can be log-transformed in order to avoid possible distortion of the results (Freudenberg 2003).

3.4.1 Normalisation for the Environmental Index

In measuring the Environmental Index, the reference values used are policy standards set by each country or international organisations. However, this is not easily obtainable for soil, making it the least easily assessed aspect of the environmental dimension of water reuse in agriculture. As different soil types have different structure dynamics, the proposed reference value is altered, so the definition of soil quality can only be addressed locally and in specific cases. In the EU, only a few member states have established national soil standards and as no standard policy targets for soil quality have been formed, the establishment of an EU soil-quality directive has proved difficult to achieve (Creamer et al. 2010).

Due to the current wait for better standardisation of soil characteristics for policymaking processes, the standard scoring function (SSF) has been adopted for this study (Wymore 1993), which is commonly used for the valuation of the soil quality. Often a linear relationship between the normalised and the physical values is assumed, however, the effect of each factor to the quality of the soil is not as straightforward; the reason for selecting this method is the presented S-shaped curve - indicating a smooth transition of the scores. This smooth transition can better represent the dynamics present in the soil structure (Dengiz 2019; Wardle 1994; Qi et al. 2009; Armenise et al. 2013).

The normalised scores range from 0 to 1, with the scores being assigned according to the type of SSF curve. There are many SSF types: each describing a different relationship between the values and the associated scores. In the EI, three SSFs are used (Figure 5), namely More the Better (MTB), Optimal Value (OV) and Less the Better (LTB). For example, heavy metals have an LTB relationship to soil quality (SSF9), which means that the lower the value of the assessed heavy metal in the soil, the higher the soil quality and hence, the higher its normalised score. Alternatively, the pH follows an OV function (SSF5), usually with an optimal value ranging from 7 to 8, depending on the soil type.

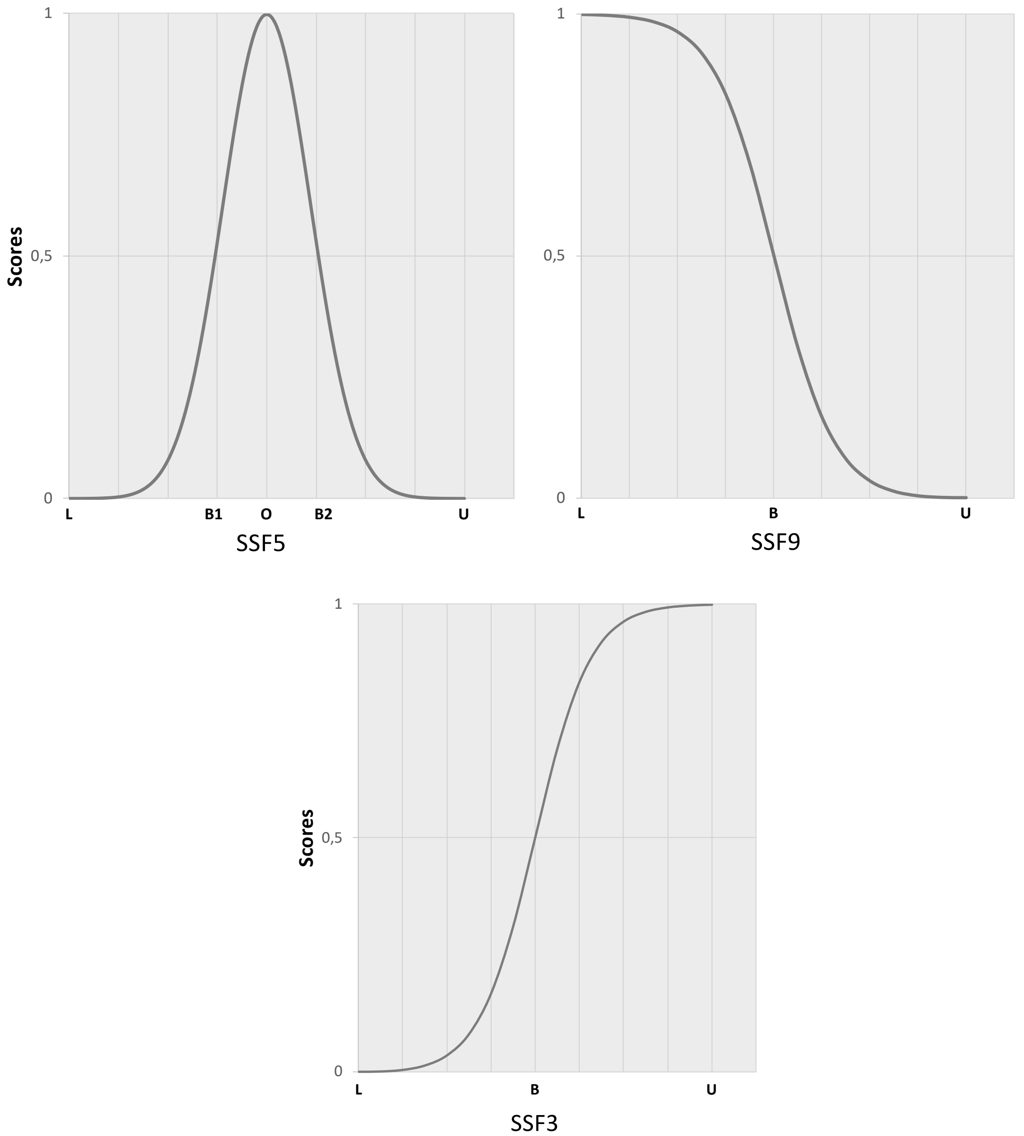

Figure 5: Standard Scoring Functions (SSFs) used for the Environmental Index. SSF3 shows a MTB function, SSF5 shows an OV function and SSF9 shows a LTB function. Graphs adapted from (Wymore 1993).

Although the relationship usually adopted for groundwater, surface water, and wastewater quality is either linear or dichotomic (Castoldi and Bechini 2010), the indicator factors are also normalised with the functions analysed above - thus allowing for a sub-index with homogeneity in the normalised values.

3.4.2 Normalisation for the Socioeconomic Index

Reference values for the SEI are also challenging to identify due to the social component being abstract, which in turn further complicates defining an optimal value. However, each country sets its own social well-being goals, and it is on these that the reference values are based. The observed value is compared to predefined target values, which in this case, are policy targets set by governmental regulations in the form of ratio:

$N_i = \frac{xi}{ti}$, when an increase in xi has a positive impact on the SI

(More the Better: MTB) and

$N_i = \frac{ti}{xi}$, when an increase in xi has a negative impact on the SI (LTB)

where N_i is the normalised value, t_i the target value, x_i the observed value and i the indicator factor (Zhou et al. 2012).

3.5 Weighting

Each indicator factor is then assigned a weight, which is given according to the importance of the indicator factor to the sustainability outcome. There are three types of weighting approaches: statistical, participatory, and equal weighting (Table 5) (Mayer 2008; Mendoza and Prabhu 2000; Nardo et al. 2008; Paracchini et al. 2008).

Table 5: Weighting approaches

Approach	Description
Statistical	Use statistical analysis to assign weights to the factors, based on their overlapping information. The first approach includes techniques such as Principal Component Analysis (PCA), Regression Analysis, Data Envelopment Analysis (DEA) and Unobserved Component Model (UCM).
Participatory	Assign weights based on the perceived importance of each factor to the overall index. Participatory-based approaches examples are the Budget Allocation (BA), Analytical Hierarchical Process (AHP) and Conjoint Analysis (CA).
Equal Weighting	Equal weight on each factor is assigned.

Some indicators may be interrelated, meaning that they might measure the same aspect to either a part of the full extent. If this interrelation is high, then double- or over-counting one aspect of sustainability is probable. This makes some weighting approaches less suitable for such cases, an example of which is the Equal Weighting Approach (Freudenberg 2003). The most common weighting method used in sustainability indicators is equal weighting, whereas the most common statistically-based method is PCA. Regarding the participatory methodologies, public opinion was mostly used for the assignment of weights (Gan et al. 2017).

3.5.1 Weighting of Indicator Factors, Indicators, and Indices

Equal weighting has been decided upon for the weighting of the indicators and the sub-indices. This means that all indicators have equal importance to each sub-index, and each sub-index has a 0.5 weighting factor to the SI.

The indicator factors are weighted through PCA; statistical approaches are appropriate to reduce bias in weight assignment, and therefore, multivariate analysis has been selected for this step; multivariate analysis is the statistically simultaneous analysis of the relationship of multiple factors on a specific aspect. PCA is a statistical technique that aims to explain the relationship among different indicator factors and group them according to their common dimension. This approach is ideal in situations where a large number of indicator factors is used, in which the dataset must be reduced into the core factors that explain most of the studied aspect (Hair et al. 2014). PCA has been widely used to measure water and soil quality (Hou et al. 2016; Lima et al. 2013; Masto et al. 2008), as well as in agricultural sustainability assessments (Roesch et al. 2017; Tiewtoy et al. 2011; Sands and Podmore 2000).

The objective of PCA is to explain the variance of the data, which is achieved through:

a. Identifying which factors explain the overall variation.
b. Finding the linear combinations of these factors – called Principal Components (PC) – that are simultaneously uncorrelated to each other and that explain the largest portion of the variance.

Each PC is a linear combination of several indicator factors:

$$PC_i = w_{i1}x_1 + w_{i2}x_2 + \cdots + w_{ij}x_j$$

where w_{ij} is the associated weight of each factor x_{ij}.

3.6 Aggregation

Following the weighting, the indicator factors are aggregated to form the final index. This is done in three stages: first, the indicator factors are aggregated into indicators, then the indicators are aggregated to form the sub-indices individually, and finally the two sub-indices are aggregated to form the SI.

The aggregation methods that are used in the majority of sustainability indices development are the linear additive and the geometric aggregation. Each of these methods is suitable, based on the characteristics of the datasets. The linear additive aggregation (or weighted arithmetic mean) is the most popular method used in both sustainability indices and water quality indices (Juwana, Muttil, and Perera 2012; Vasanthavigar et al. 2010). Furthermore, it is preferable when trade-offs between the indicator factors are not defined; trade-offs between the factors are absent when the low value of one factor is compensated by the high value of another factor. On the other hand, the geometric aggregation is

more suitable when trade-offs among the factors are present, or not enough information on the underlying interlinkages among the factors exists. However, the geometric aggregation does not account for full compensation of the trade-offs, and sensitivity analyses cannot be employed with errors of the factors (Langhans, Reichert, and Schuwirth 2014; Gan et al. 2017; Nardo et al. 2008).

Due to the theoretical basis of the index represented here, it was decided not to specify methods that have been selected for the aggregation step, as the appropriate methodology can be decided after the analysis of the data. In the formulas presented in Table 6, x_i denotes the indicator factor and w_i the associated weight, where $0 \leq \sum w_i \leq 1$.

Table 6: Aggregation methods

Method	Formula
Linear Additive	$X_i = \sum_{i=1}^{n} w_i x_i$
Geometric	$X_i = \prod_{i=1}^{n} x_i^{w_i}$

3.7 Robustness of the Analysis

For the development of the index, scientific evidence and judgement derived from personal knowledge was employed in the selection of the indicator factors and methodologies - but this means that the outcome could be subject to error and could also lead to policymakers receiving misleading information if factors are not correctly selected. It was therefore deemed important to seek validation and monitor its vulnerability to changes, such attesting the index with respect to its normalisation and aggregation methodologies. The comparison of the results of the index-based assessment under different normalization and aggregation approaches is recommended.

A suggested robustness measurement for the sustainability index applies the combination of sensitivity and uncertainty analysis (Nardo et al., 2008; Saisana et al., 2005). The applied sensitivity analysis aims at finding how much each variation in the input to the index affects the final result, while uncertainty analysis tries to identify how much the uncertainties that arise from the different selection criteria are affecting the overall result.

4. Discussion

The definition of sustainability varies according to the field in which its application is assessed; culminating in both case-dependent and subjective concepts of sustainability. The subtle line that separates the three dimensions of sustainability (economic, social and environmental) means that interpretation of interlinkages between the dimensions is often unclear. The task of identifying the appropriate social and economic indicator factors to assess the sustainability of wastewater reuse in agriculture throughout this study was challenging; strong interconnectedness between these dimensions was found to be present, as both dimensions have an anthropic nature, i.e. they are defined by human activities. For this reason, it was determined that these two dimensions should be assessed in combination, as opposed to the environmental dimension, where core attributes are clearly distinguishable.

As the indicator factors are very often interrelated to one another, overcounting a specific impact can potentially occur. In order to reduce this risk, some indicator factors were not incorporated. The exclusion of indicator factors that could provide further information on the impacts of wastewater application was further boosted by the fact that the ease of use of the SI lies in its ability to be comparable between regions, in the simplicity of its outcome, as well as in the availability of relative data.

Additionally, crop quality has also been omitted from the Environmental Index, as the impacts of poor crop quality are translated into financial losses for farmers and impact the health of the community. Furthermore, the availability of data (or lack thereof) has resulted in indicator factors measuring emerging pollutants (EPs), such as Pharmaceuticals and Personal Care Products, being excluded. The measurement methods for these pollutants are still costly, and therefore, many developing countries do not have the financial means for their monitoring (Luo et al. 2018); including emerging pollutants in this study would have prohibited the index from being applied in these countries. Fortunately, now that the importance of these indicator factors is gaining recognition in academia, measurement methods will gradually become more mainstream, which will allow for their application on a broader geographical scale.

5. Summary

In creating this index, we attempt to bridge the gap between a holistic sustainability assessment and the current indices-assessing practices in water reuse in agriculture.

Primarily, the environmental dimension was assessed and integrated with the socioeconomic dimension. Indicators assessing the quality of environmental aspects, such as soil and groundwater, were combined with indicators assessing social and economic aspects, such as equity and income, in order to provide a more holistic view of the impacts of wastewater applications in irrigation. Secondly, the selected indicator factors have been widely recognised and are relevantly attainable. Furthermore, their number has been minimised via both making a selection from the already existing pool, followed by PCA. Consequently, the

final set of indicator factors identified have allowed for broader applicability and availability in their use. The index can be applied at a regional or national level, thus connecting the two boundaries of assessment.

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