Identifying and implementing circular applications of agri-residues

A circular evaluation framework for assessing impacts and circularity of different agri-residue applications

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PO box 17, 6700 AA Wageningen, The Netherlands, T + 31 (0)317 48 00 84, E info.wfbr@wur.nl, www.wur.eu/wfbr.

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Contents

Summary

This report describes and explains a Circular Evaluation Framework that supports the decision making process in the implementation of processes for the valorisation of agri-residues or by-products. Implementation of this framework leads to a quantitative comparison of circularity, socio-economic impact, environmental impact and implementability for alternative processes. Based on such evaluation and case-specific prioritization, informed decisions can be made about process improvement or implementation support. New, is the quantification of circularity, which is laid out in this report. Based on the components of a by-products, process characteristics and application hierarchy, utilization paths are evaluated and scored, allowing for a quick comparison as well as an in-depth analysis.

The application of this framework is demonstrated on four representative case studies, for which data was gathered either directly by specialists with local connections or interviews with people involved in the implementation of new processes (Transcripts of interviews are attached to the annex). Finally, a quick description of the process of using the framework is given in a decision tree, and a flyer, that summarizes the most important aspects of using this framework on one page.

1 Introduction

The Ministry of Agriculture, Nature and Food Quality (LNV) has the ambition to enhance circular practices in the Dutch agriculture and food industry and also to promote the use of relevant knowledge and technology developed by the Dutch agri-food cluster through co-creation in countries where agricultural counsellors are active. With this, new business opportunities would be created for Dutch companies and knowledge institutions, whereas at the same time, LNV sees circular agriculture as an important strategy in strengthening economic perspectives for farmers and entrepreneurs in developing countries, and in making food systems more sustainable (Department Agriculture Nature and Food 2018).

An important pathway to increasing sustainability in agriculture is the circular application of the residues that are generated in agriculture. Residues can be re-used or recycled and more value can be added. In linear agri-food supply chains, residual flows are often not or only sub-optimally (re-)used, which often results in major environmental problems and cost. However, recent examples and experiences illustrate there is much to be gained by recycling, re-using and valorising agri-food residues, as it may reduce environmental pressure and offer local employment and income opportunities as well (for examples from developing countries see: Van Berkum & Dengerink, 2019; Wing Yin, Yu Bon, & Ming Hung, 2017 and for examples from the E.U. see: Lee et al., 2017). At the same time, these examples indicate that, whether economic viable business cases are ecologically sound, or vice versa, ecologically sustainable recycling practices would provide economic benefits, depends on the specific nature and features of the residue, its alternative use(s) and the locally specific economic, social, institutional and technological opportunities. Important questions are how policy can promote circular agriculture and how initiatives to invest in circular application of residues should be assessed. This project aims to design an assessment framework that identifies the performance of different applications of agricultural residues based on ecological, socio-economic, local implementability and circularity indicators.

The Sustainable Development Goals (SDGs) are the international policy guidelines for Dutch aid and trade policy; see "Voedselzekerheidbrief" (Ministry of Agriculture Nature and Food. 2018) Agriculture plays an important role in taking up the 17 global challenges of sustainable development (United Nations n.d.). In optimising the use of biomass, circular agriculture improves resource efficiency. However, in order to contribute to sustainable development, policy measures and/or investments promoting recycling and re-using natural resources should not compromise one of the three (that is, social, economic *and* environmental) sustainability dimensions. In order to address these three sustainable dimensions *simultaneously*, the interventions proposed should take a food system approach. The food system approach is increasingly used as a concept to understand and shape transformative action to enhance food and nutrition security and to contribute to SDGs (Ruben, Verhagen, and Plaisier 2018). A food system approach maps the *activities* in our food system (production, processing, distribution and utilisation of food), analyses the *relationships* between them, and the *outcomes* of these activities in terms of food and nutrition security, socio-economics (e.g. income and employment; distributional effects) and the environment (e.g. biodiversity, water and soils). A systems approach to circular agricultural provides insights into the potential contributions of all stages of agri-food supply chains in achieving the objective of narrowing or closing cycles of natural resources, and identifies useful leverage points for promoting circular agriculture. One of the key characteristics of a food system analysis is that technological innovations are considered in close relationship to the behavioural changes required to guarantee their sustainable adoption (Ruben, Verhagen, and Plaisier 2018). Above all, the food system approach provides a framework for assessing social, economic and ecological outcomes of an intervention simultaneously, explicitly acknowledging the trade-off or synergies between different – sometimes competing – goals.

This study discusses and analyses cases valuing residual biomass flows for its circular, economic, and environmental impacts, plotting the cases with regard to the functionality and technical efficiency of the recycling process and with regard to the implementability (in terms of technical capabilities, institutional strength and opportunities, and other factors that affect processes to practically execute the intended investment) of the case. This results in a Circular Evaluation Framework that can help the decision making processes of agricultural counsellors, stakeholders and experts by identifying more circular opportunities (given the local context) for economically viable business cases of re-using agricultural residues with sound ecological impacts. Moreover, the framework helps to identify and address obstacles for exploiting opportunities, that can give rise to policy interventions and/or private business investments in order to overcome those obstacles. The process on finding alternative applications described in this report is based on earlier research done by WFBR and a number of interviews. We want to specifically mention the useful interviews with Paulus Kosters (Royal Cosun) and Johan Sanders (emeritus Professor Wageningen University).

2 Assessing different options of agro-residue valorisation

Comparison of different applications from agri-residues allows identification of the most favourable solution. Whichever solution is deemed most favourable, really depends on the focus, context and priorities in each case.

This work makes use of indicators highlighting the application opportunities or functionality of (components in) the biomass, based on novel and ongoing research at Wageningen UR (Spijker et al. 2020; B. Elbersen et al. 2019). These indicators quantify the hierarchy of agri-residue uses. It is important to note that focus is laid on the components of the biomass (protein, fibre, carbohydrate, minerals, etc). The priority of use of an agri-residue will be different for a residue high in protein compared to a residue high in fibre.

Assessment of different valorisation options requires comparison of the status quo with possible alternative uses. This comparison is facilitated with the ‘Circular Assessment Framework, which is described in the following section. The framework consists of a tool to identify and judge a number of indicators, and a visual representation of the overall processes. The indicators are categorized into four domains: circularity, socioeconomic impact, environmental impact, and implementability. For comparative purposes we opted to analyse four indicators for each category, resulting in 16 indicators in total. It may be required to choose, separate or redefine some indicators for specific cases. For example, in some cases air pollution may be relevant and water pollution less relevant or the other way around.

The developed assessment framework compares different uses of an agri-residue on a relative scale compared to the current situation. For each category a question is asked, i.e. *does the alternative application of the agri-residue design support rural development?* The answer is given in form of a (short) explanation and a score between -2 and +2. The scores (-2, -1, 0, +1, +2) can be interpreted as much worse, worse, neutral (i.e. nothing changes or impact is similar), better, and much better. Each indicator is scored accordingly, the value for the status quo is 0. The indicators are listed in Table 1 together with an exemplary score.

Table 1 Domains and categories as well as examples for scores used in the circular valorisation tool

Domain	Category	Example score
Circularity	Functionality used	1
	Biomass utilization efficiency	1
	Possibility of reuse	1
	Land sparing	1
Socio-economic impact	Value added	1
	Profitability	-2
	Job Creation	2
	Rural development	2
Environmental impact	GHG Mitigation	1
	Soil quality	2
	Biodiversity	1
	Water quality / air quality	1
Implementability	Technology development	1
	Presence of infrastructure	2
	Presence of enabling policy	1
	Regulations, subsidies, standards	2

Together with all-round scores of 0 for the status quo, the scored values for the alternative valorisation route listed in Table 1 are used to visualize the comparison in Figure 1. by using this comparison and visualization, it also becomes clear which aspects to improve in order to optimize the overall impact.

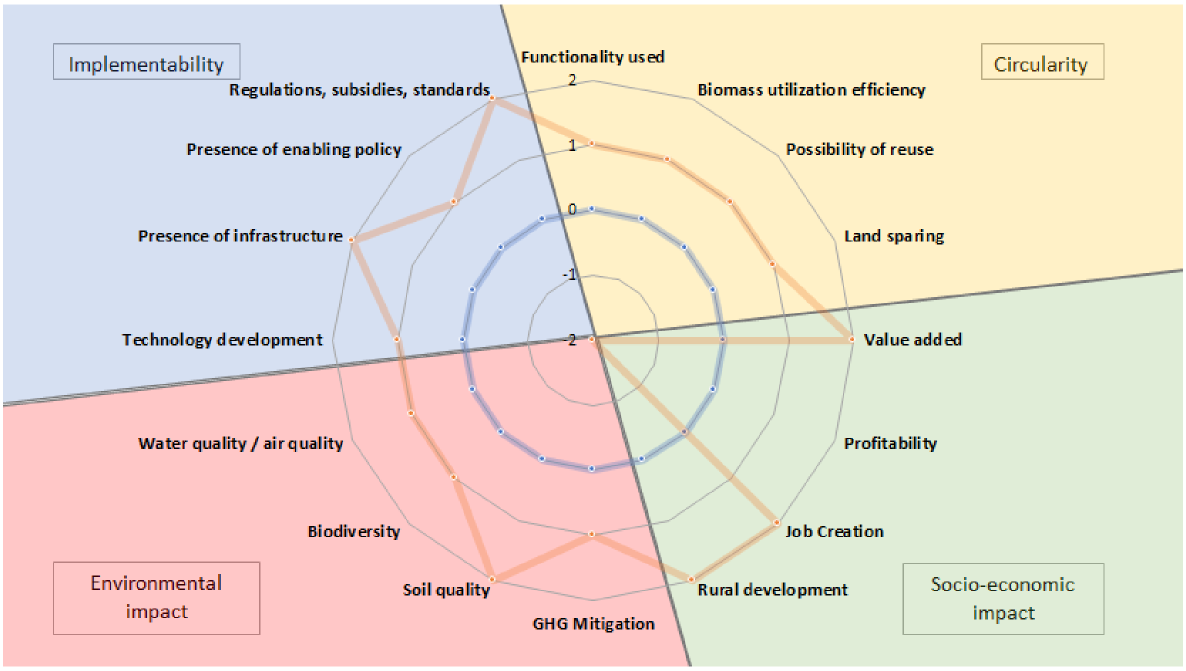

Figure 1 Example of visual multicomponent comparison framework for circularity assessment

In the following sections, for all four domains each category is explained.

2.1 Circularity

In our definition, circular valorisation of residues indicates to which extend the functionality of the biomass or the components thereof have been used (efficiently) and have been conserved for re-use. This will be further discussed in Chapter 3. Here we discuss briefly the 4 aspects that can be weighed here. Analysis of circularity for the framework requires answers to four sub-indicators:

- Functionality used: Has the functionality been used and at what level?

    It judges if the newly proposed use of the agri-residue maintains functionality (much) better or (much) worse than the current application or use. The scoring shows if the new application is higher or lower in a hierarchy of applications (see Chapter 3, Figure 2, Figure 3, Figure 4 and Table 2). To assess this score the composition of the agri-residue has to be known. The Feedipedia website (www.feedipedia.org) or the Phyllis database (https://phyllis.nl/) may provide information on composition of agri-residues that can be used for feed or for energy generation respectively. Keep in mind that residues also need to be used as circular as possible.

- Efficiency: What is the technical efficiency of the use?

    The efficiency of conversion is very relevant. The residue may be applied at a high circularity level. If only a fraction is used the score should be lower. Heating a house by burning wood can be done at an efficiency between 10% for an open fireplace and 80% for a new efficient closed wood stove. A process may score high on the functionality used, if the efficiency is low and the majority of the material is lost or may require a lot of effort /energy to be re-used, this should be taken into account. Depending on the nature of the process, input materials (i.e. agri-residues and additional materials) and products, prioritization on process aspects may tip the scales in favour of one process over another.

- Re-use potential: Can the biomass (or components thereof) after initial use be reused? And at what functionality level?

    This indicator expresses the next step of the biomass after use. A good example is the use of wood for furniture. The major functionalities of wood are kept intact, when it is crafted into something else, i.e. another piece of furniture. Or can it only be used for an application down the ladder, such as burned for energy generation?

- Land sparing / natural resource savings: When products are used for making products this can reduce the need to use more land, water and other finite natural resources.

    For an example see discussion on circularity of wood cascading and saving of wood or land in section 3.2.

2.2 Socio-economic impact

Socio-economic impact relates to the expected social and economic impact of the (proposed) project in comparison with a baseline situation in which this project is not yet in place. On the economic level, circularity in activities can be lucrative. It can improve resource productivity and competitiveness by recovering value from items that otherwise go to waste (Green Alliance 2015). In general, positive impacts of circularity are identified in sustainable resource saving, economic growth, growth of employment, innovation stimulus and changing demand (Het Groene Brein 2021).

Among the indicators that judge socio-economic impact domain: rural development, job creation, profitability and value added.

The questions to be asked in order to use the socio-economic impact indicators are:

- Rural development: Does the proposed project contribute to economic activity beyond the project itself? Is the project expected to boost the well-being of surrounding communities?

  Circularity allows for environmental sustainability (natural resources sustainability) and socio economic sustainability to be paired up, strengthening economic rural development (Kitchen and Marsden 2009). Specifically, within agri-residues processing activities, there might be considerable positive effects for rural communities. For example, the conversion of manure into organic fertilisers, energy sources or new bio-based products might benefit rural communities with additional value generation and job creation (see following indicators).

- Job creation: Does the project create a situation with more employment opportunities than in the baseline situation without the project?

  Selling products for reuse and manufacture supports more jobs than not performing any circular activity; in the context of sustainable agri-food systems, these are mainly green jobs. For example, by landfilling waste, the value is lost as the materials are thrown away. Instead, for example by composting, job is created (0.1 jobs per thousand tonnes of waste) (Green Alliance 2015)

- Profitability: Does the project have a higher profitability than the agri-residue processing activities it replaces?

  Profitability can be looked at in terms of profit generation and reduction of inputs costs. It is generally important for an activity to be economically viable, thus generating profit and not incurring into bankruptcy. However, in some cases, the cost of implementing agri-residue processing activities are higher than the revenues. This requires government subsidies or, in general, additional finance from external parties to keep the businesses running, resulting in unprofitability of the activity. In case of subsidy dependency, it should be clear that the subsidy will remain in place.

  In terms of reduction of inputs costs, circularity allows for resource saving by reducing demand for primary raw materials and expenses for material resources. (Fellner et al. 2017). This can result in increased profitability as production costs are reduced giving room for more profit. Therefore, profitability of the project is strictly connected with the indicator of “natural resource savings” explained in the circularity section.

- Value added: Is there new economic value creation in terms of products from the project?

  Value added is here considered in terms of economic value created out of materials that otherwise would become waste. To remanufacture, to repurpose, to recycle and lastly to recover are activities that allow to convert secondary used materials into finished goods (Pavel 2018). As an example, to create organic fertiliser from household waste is a way of adding economic value to a waste material and create resale value that works as input for subsequent activities in the value chain (fertilising the soil).

  Adding value as an economic impact of circularity gives room to innovation, by incentivising creative ways of giving value to waste materials.

2.3 Environmental impact

Environmental impact relates to the expected environmental impact of the alternative valorisation route (including replacement of alternative resource) in comparison to the status quo. An accurate assessment of each indicator may actually require extensive research and modelling, but a rough estimate should lead to satisfactory results for the qualitative comparison. The indicators for comparison of environmental impact are greenhouse gas (GHG) mitigation, soil quality, air quality and impact on biodiversity.

The questions to be asked and answered in order to use the environmental impact indicators are:

- Does the proposed valorisation lead to less GHG emissions than would be the case in a situation without the proposed project?

  Answering this question with accuracy requires extensive calculations on many aspects of the two processes. GHG emissions for the process and possibly construction of infrastructure need to be accounted for. Also, indirect GHG emissions or reduction thereof (including replacing traditional production pathways for the intended functionality) would be tallied in an accurate calculation. For the purpose of this tool, only an estimation for comparison is needed.

- Does the proposed valorisation lead to better soil quality or reduced soil degradation compared to a situation without the proposed project?

  Many agri-residues are produced directly on or nearby the soil they were growing on, i.e. the leaves of beets. It has been, and in many instances arguably still is, common practice to separate product from agri-residue directly on the field and leave the latter on the field but it can also end up in a landfill nearby. This may lead to a variety of problems, one of which is discussed in section 4.2. A residue left in the field can have a value for maintaining soil quality. Without alternative measures like applying manure or growing a cover, the effect may be negative.

- Does the proposed valorisation lead to improved air quality (or water quality) compared to a situation without the proposed project?

  This may be a relatively easy to assess as it often is the driver to find alternative uses for agri-residues.

- Does the proposed valorisation lead to more biodiversity (or less biodiversity loss) compared to a situation without the proposed project?

  This point may also require extensive studies if answered with a high accuracy. Changes in biodiversity are not always easy to quantify, but again, a general notion should lead to sufficient results. Biodiversity loss is often associated with changes in land use, mostly towards arable land. In case of the two examples (in Chapter 4) food grade protein is produced without requirement of more land. The increase in productivity without further land use, should indirectly lead to reduced land requirements in other places, for protein production (whether it is the adjacent cow pasture or a South American soy bean plantation).

2.4 Implementability

Implementability is the last section of this chapter, but also the most important section. From this analysis the action plan can be distilled. Following the description of implementability is a separate section that details issues with implementation of new processes that re-occur on a regular basis.

The term implementability or applicability describes the individual, organizational, or system barriers that could challenge adoption, or instructions for local needs assessment of guideline users (Gagliardi and Brouwers 2012). In other words, it relates to the extent whether proposed changes including investment for processing the residue for re-use or recycling can actually be made, and refers to factors or domains that may act as potentially restraining or blocking the intended investment in case these are insufficiently developed or available.

For the application of the circularity tool, it is important that implementability evaluate each scenario from the start of a baseline situation (i.e. situation before the implementation of project).

Among the factors that judge the implementability are:

- Access to the required technologies, knowledge and skills to operate these. This refers to:

  Are the required technology, knowledge and skills available and at what costs? If the technology, knowledge and skill capacities necessary requires further development, what would be estimated costs to make it available and applicable in the local context?

- Presence of necessary physical infrastructure and business networks. This refers to the capacity, reliability, access to and costs of
    - Roads, railways, rivers, canals, airports, and other transport routes
    - Energy (power stations, electricity networks), internet and other communication facilities
    - Business networks and services that are adjacent to the residue processing activity (such as transport services, knowledge providers, financial services, technical input suppliers, upstream industries and/or farmers that may purchase the recycled residue)
- Enabling government policies, regulations, subsidies, standards
    - The current legal framework itself; if a (national or local) government wants to change the legal framework it has to go to (national or local) parliament. This also includes industry standards. Policy and laws can be in conflict, up to a point where regulations required to change for the implementation of the project.
    - Subsidies, taxes, and prohibitions/bans; that is, what is possible under the current legal framework.
- Availability of financing
    - This includes local or national access to credit and investment banks
    - Individual characteristics like, lack of liquidity, personal access to credit, the value of financial assets.
    - Worthy of consideration here is that investments into processes that involve new technologies are higher risks for investors, which may influence financing availability and certainly financing conditions.

The implementation quadrant is considered both to be part of the evaluation of the investment proposed (a low score would imply many difficulties in the actual implementation of the investment) and to give way to possible solutions for making residue valorisation investments successful. Indeed, factors mentioned in the implementability domain can be considered leverage points for actions or interventions that will help to improve the potential socio-economic, environmental and circularity effects of the residue processing investment. That means that, when a circular investment scores low on one of the four implementability domains, the next step would be to identify the main bottlenecks that cause such low scores, using the four aspects mentioned in the implementation quadrant as main domains to focus on. Once addressed a barrier to a successful investment, more specific recommendations and/or actions can be formulated. At that stage the role and action perspective of Dutch agricultural counsellors should be identified as well, as he/she would be able to assess whether and if so, where support in the context of the Dutch foreign aid, trade and investment policy would be appropriate.

2.4.1 Implementation issues

As we learned from using the circularity tool, the background research for the case studies including the conducted interviews certain reoccurring issues hinder implementation. Generally, implementation is putting to use or integrating new practices within a setting (Gagliardi and Brouwers 2012; Rabin et al. 2008). Naturally, new practices tend to meet resistance, therefore identifying barriers that could challenge the adoption of the new practices/ project beforehand improves the implementation during practical roll out.
Literature has identified several factors associated with the speed and extent implementation. Factors can be classified as the characteristics of the intervention, characteristics of the adopter (organisational and individual), and contextual factors (Rabin et al. 2008).

Characteristics of the intervention consider attributes that are likely to influence the speed and extend of the adoption (Rogers 1962). Next to complexity, for example, some projects might have a relative advantage and be more cost-efficient to implement.

Other projects might be compatible with other innovations or can happen simultaneously using different residues. In some cases, outcomes might be less tangible/observable (Rabin et al. 2008).

Characteristics of the adopters can be discussed at different levels depending on the project. Are the actors, individual farmers, organisations, or community stakeholders? Attributes of the actor involve may include its size, formalisation, perceived complexity, and readiness for the implementation of the innovation (Rabin et al. 2008). Regarding individuals, characteristics such as attitudes and behaviour of the decision-maker are key. These include individual concerns and motivations, which may also determine the uptake and use of innovation (Rabin et al. 2008).

Finally, contextual factors shape the implantation of a project. These include the political, social, and organisational settings, social support, legislations and regulations, social networks, norms and culture (Rabin et al. 2008).

This report analyses four case studies with diverse applications with very different results. On the one hand, the nutrient recycling from household waste in Accra, Ghana benefits from the presence of a public-private partnership (business networks around the composting activity) that highlights the positive side of implementability. As a result, there is a positive impact of the different indicators with relatively high implementability score.

On the other hand, in order to convert pineapple residues into biogas for electricity in Costa Rica, a market has to be created. Local legislation does not allow storage of electricity. Therefore, a successful application of biogas production is not in line with the current policies in place, preventing a profitable activity.

Cases in the Netherlands are recovering protein from sugar beet leaves and from starch production side streams. In the case of protein from sugar beet leaves, implementability was hindered by legislation that reduces fertilization possibilities and infrastructure will become important in the coming phase of scaling up from the pilot plant. Recovery of protein from starch production side streams shows an efficient process, where the vast majority of protein is captured. Here, the main implementation issues were that the required technology was not fully developed and extensive research had to be done.

3 Circular valorisation of agri-residues

Agricultural residues are often considered as waste. The residues are disposed of, whereby potential value and essential nutrients are lost, or at least not used optimally. In many cases disposal of residues has negative environmental impacts. For example, burning of residues leading to considerable air pollution, discharged liquid residues may lead to pollution (i.e. eutrophication) of waterways or disposal leads to odour nuisance or worse, hygiene problems. Alternatives to the current disposal or application of residues need to be identified and assessed. In this section, the different natures of residue categories are discussed, followed by a method to quantify circularity as tool for comparison of alternative valorisation routes. For the quantification of circularity in the comparison of residues made up of different components, it is important to establish a hierarchy of by-products and components, which is discussed, before a short description of the history of residue valorisation at the end of this section.

3.1 Categorizing agricultural residues

Agricultural residues and waste can be categorized in primary residues, secondary residues and tertiary residues. For the Netherlands these residues (agricultural residues and other) were assessed in a report by Koppejan et al. (Koppejan et al. 2009). Below the categories are discussed.

3.1.1 Primary residues originating in the field

Primary residues originate in the field and are produced during peaks at harvest time. In general, these residues can be left in the field where they have a value for the soil returning nutrients, mainly nitrogen (N), phosphate (P), potassium (K), and others such as Ca and Mg as well as micronutrients of value to plant growth. The residues also contribute to adding soil organic matter to the soil which is important for water holding capacity, aeration, soil penetration and nutrient holding capacity. Leaving these residues on the soil can also have negative aspects such as hygiene problems and difficulty with sowing a new crop (W. Elbersen and Keijsers 2019). Farmers will want to remove and preferably sell it for a profit or they choose to burn the residue in the field leading to air pollution and loss of nutrients (e.g. nitrogen) and carbon which could have had a value for the soil or for other purposes (Bakker et al. 2013).

Examples abound:
Rice straw in northern India is often burned in the field the October/November leading to very problematic air pollution (W. Elbersen and Keijsers 2019). The reason for this is that the field has to be cleaned soon after rice harvest to sow wheat. In Egypt such need of a short turnover time between rice and following crops is also the main reason for rice straw burning (Bakker et al. 2013). There is not enough labour available to collect and bale the straw in a short period. Current alternative applications of the straw are not possible or do not provide enough value. There is also an abundance of wheat straw available which is more attractive as cattle feed. Also the carry-over of diseases can be avoided and the value of nutrients (in the straw) is low because of subsidized fertilizers. Overall farmers choose to burn straw and stubble in the field even though this has been banned. The problem of rice straw burning has increased in recent decades due to rice straw expansion (as proportion of total crop production in the region) and yield increases following government policies and incentives. Other example is the pollution problems caused by the removal and disposal of pineapple field residue in Costa Rica which is discussed further on in this report.

3.1.2 Secondary residues, produced during processing of agricultural products

Secondary residues are produced during processing in a factory. Here they generally are produced in larger quantities over a longer period of the year. They can be fluids containing diluted organic materials and nutrient which need to be processed before disposal.

Examples include Palm oil mill effluent or wash water of vegetable processing. They can also be solid residues such as husks, peals or any other component which is not the main product.
Examples are sunflower husks used for feed or energy generation, slaughterhouse waste, empty fruit bunches and mesocarp fibre from palm oil mills, potato peels, etc. In many cases these residues have a use and often fetch a significant value often as feed but also for energy generation. Examples include sugar cane bagasse (press fibre) used for energy production and sometimes paper pulp, potato peels for feed, sugar beet fibre for feed, etc.

3.1.3 Tertiary residues are material which often have had a function and are collected for disposal

These tertiary residues (waste) are generally mixed and cost money to dispose. This category includes ‘post-consumer’ waste like municipal organic waste, kitchen waste, and garden waste. Sludges are also included in this category. The fact that the residues are often mixed makes adding value difficult. If collection of subcategories is possible this can make adding value probably easier. For example, by collecting reject vegetable products from a market place and applying adequate quality management they can still be used for dedicated food, feed or other applications. On the other hand, sludge can contain pollutants making it undesirable or impossible to even apply these sludges to the soil as a fertilizer.

3.2 Quantifying circularity

This report aims at guiding decisions on how to apply agricultural residues. The starting point is the current use of residues and the assumption of a need or desire to find a better application for the residue. As stated in the introduction a method is developed that takes the relevant factors which determine whether a new application of a residue is better than the current application into account. This concept is further explained in section 1.
The starting point of the analysis system are the general circularity principles as formulated by the Ellen MacArthur Foundation (Ellen MacArthur Foundation n.d.):

- Design out waste and pollution
- Keep products and materials in use
- Regenerate natural systems

Designing out waste and pollution essentially means that the system should be designed so that waste and resides are minimized and what is produced after optimisation is reused and does not contribute to pollution. Keeping products and materials in use has been translated in development of hierarchies for application of agri-residues and wastes.

In the Netherlands the “Ladder van Moerman” or Moerman’s ladder is generally used as an indicator of the preferred application for agri-residues (Het Groene Brein 2021). The diagram was apparently developed mostly with food waste in mind, and it does not take into account composition or efficiency of uses. On the top of the ladder stands prevention and avoidance of food waste.

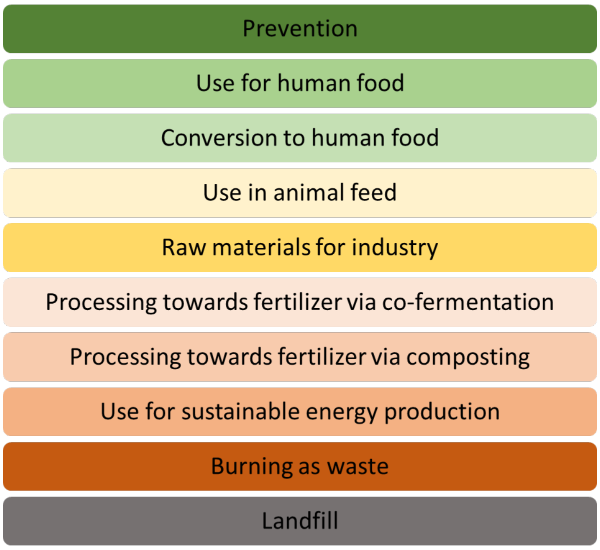

***Figure 2	Ladder of Moerman, based on (PBL Policy Brief 2016)***

More recently the desire to keep products and materials in use has been translated into the concept of cascading use of biomass. This cascading use of biomass has been extensively assessed for wood and wood products, which serves as an example. It may be best illustrated by the example of wood, by Höglmeier (Höglmeier 2015). In a model study the current situation was compared to a situation of improved cascading of wood. The improved case had a 7% lower global warming effect and savings of 14% in the annual primary wood supply of the study area while providing the same services or products. This may be translated into 14% less forest needed for the same products and services or 14% wood can be used for other purposes. Lower land use is an important contributor for the final circularity principle of the Ellen MacArthur Foundation: regeneration of natural systems.

In this present work, the concept of cascading use of wood is described using 5 levels similarly to the method used by Spijker et al. (2020). The cascade (see Figure 3) starts with wood for solid wood products (Level 4), then particle board and pulp (Level 3), Monomers such as chemicals and transport fuels (Level 2), then energy and soil improvement applications (Level 1) and finally burning the material without winning energy (bonfire) or dumping residues on a landfill (Level 0). In the process products can also be re-used for the same or similar purpose if possible or downcycled for the next application lower in the cascade.
The aim should be to efficiently apply wood first at the highest level and keep it a long as possible at a high level. Low efficiency of any process should lead to lower circularity scores. Further, occurrence of losses needs to be considered for every step. Part of the biomass is used for uses lower in the cascade i.e. wood trimming and saw dust is used for particle board, chemicals or energy. The principle is that breaking down the material reduces the options for applying the material without more efforts needed. The options for using the material are reduced or to put it differently.
For the case of wood it was assumed that wood could be used at four levels of decreasing functionality, plus a zero level that indicates loss serving a function:

4. Uses in which the wood functionality is maximally retained i.e. a table, wooden shoes, etc.
3. Uses in which functionality is decreased i.e. particle board or paper
2. Uses in which wood is broken down to monomers i.e. chemicals, pyrolysis oil, etc.; electricity is also included in this category
1. Energy uses i.e. heating
0. Wood is lost without providing a service, i.e. landfill, bonfire, etc.

The resulting hierarchy does not mean that applications at a lower level are bad, but rather that higher level applications should be first in line. The system describes what should be done first, not how important a given application is per se. Processing material, material losses, and moving to lower circularity scores cannot be avoided completely, but processing needs to be done efficiently. However, with every step down the circularity ladder, degrees of freedom are lost. Up-cycling, while sometimes possible, can be complicated and almost by definition takes energy and effort. It is important that all resources are preserved and are not lost, which often goes hand in hand with pollution problems.

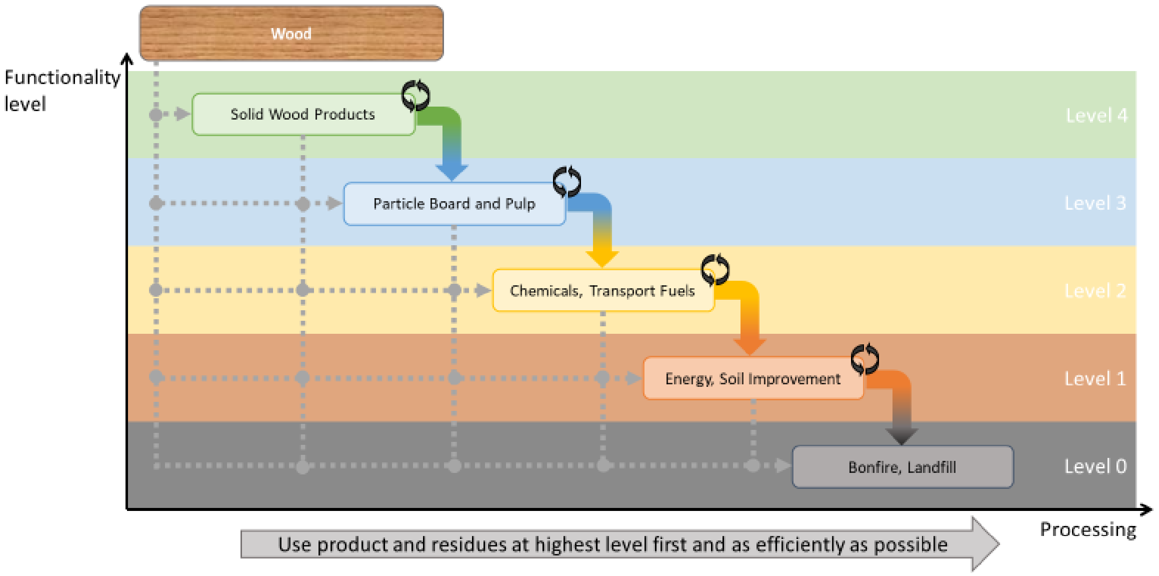

Figure 3 ***Illustrating circular cascading approach in the use of wood, aiming to use the quality of the source material as efficiently as possible. Based on (Höglmeier 2015) and (Spijker et al. 2020)***

Overall we can define four indicators for circularity of biomass use:

A process in which biomass is (re-)used while maintaining its **level of functionality** leads to a more circular process than a process in which a functionality is not used or used to a lesser degree. In addition to the nature and importance of the use, also the **efficiency** of the use (kg input/kg output or MJ input/MJ output in case of energy applications). Many applications of biomass preclude further cascading therefore also an indicator is needed for the **re-use potential** at a certain level. Finally, an indicator of land use saving (**land sparing**) would be in place here (if it can be estimated). As in the example by Höglmeier, this can be estimated and obviously is an important indicator for sustainability (Höglmeier et al. 2015).

With these 4 indicators circularity of different applications can be compared for virtually all agricultural (by-)products, as exemplified for wood. The general approach for any agricultural by-product is illustrated in Figure 4.
However, wood is composed almost entirely of lignocellulosic material (fibre) and it contains very little other materials such as protein, fat, starch, sugars, and nutrients such as phosphate and potassium. The presence of more components in the biomass makes the evaluation more complicated. Not all components will have a similar circularity hierarchy. The application for food and feed is not relevant for wood (fibre) but it is for proteins, fats, and carbohydrates.

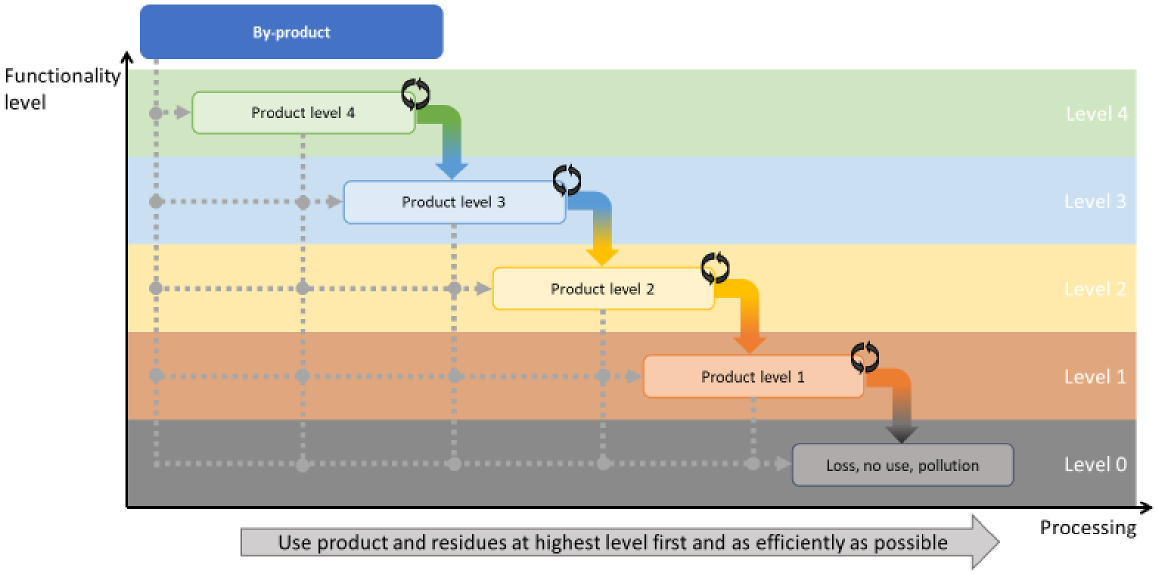

Figure 4 ***Illustrating general approach for circular cascading of a given by-product, aiming to use the quality of the source material as efficiently as possible. Based on (Höglmeier 2015; Jarre et al. 2020; Spijker et al. 2020)***

3.3 By-product and component hierarchy

Biomass is generally made up of different components such as fibre, protein (nitrogen), fats and oil, carbohydrates (starch and sugars), minerals such as phosphate (P), potassium (K), and maybe other important components. These components may have different cascade order; what is a relatively high-level application for one component may not be a high level application for another application. This notion is not really considered in most valorisation hierarchies (see discussion below).

The hierarchy of functionality use generally follows the approach: *food over feed*. Food applications prevail over all other applications, as far as food applications are applicable. However, in the hierarchy local considerations can influence prioritization. An example of a logical hierarchy based on maintaining functionality is given in Table 2 for the most common components of agricultural by-products.
We explain the logic for a few of the components. If protein is used as human food, this is the highest level of application (4). Use as feed (3) is a lower-level option, since it is generally an indirect way to produce protein for human consumption with efficiency significantly below 100%, and therefore scores lower. Using protein as nitrogen source, i.e. as fertilizer, does not make use of the functionality of protein and therefore scores lower (2). A lower-level use of use of protein is energy (burning) production (1) where the nitrogen is lost. Transforming protein into biogas, as energy source is then preferred because the nitrogen can still be applied as fertilizer. The lowest score is applied if the protein is lost or emitted to the environment then the score is 0.

Table 2 *Example of a logical hierarchy based on maintaining functionality as long as possible and giving food and feed (in principle) preference over other applications*

Functionality level	Fibre	Protein (Nitrogen)	Fat and oil	Carbohydrates (starch and sugars)	Phosphate[3], Potassium[3], etc.	Other
4	Materials	Food	Food	Food	Food	Food
3	Pulp, Feed, etc.	Feed / Materials	Feed / Materials (paint, chemicals) /	Feed / Materials	Feed	Feed
2	Monomers (chemicals and fuels[1])	Fertilizer	Transport fuels[1]	Monomers (chemicals and transport fuels[1])	Fertilizer and high value chemicals	Material
1	Energy[2], Soil	Energy[2]	Energy[2]	Energy[2], Soil	Materials	Fuels[1], Soil
0	Loss, Pollution	Loss, Pollution	Loss, Pollution	Loss, Pollution	Loss, Pollution	Loss, Pollution

1. Fuel = transport fuel or electric energy
2. Energy= burned directly
3. Phosphate and Potassium generally have no energy value

Another example of circularity evaluation based on used functionality will be laid out for fat. Fat used as human food ingredient scores highest, and as with protein, fat used for feed applications second highest. Differently to protein, there are many non-food non-feed applications that make use of fat functionality, in the chemical industry or as a lubricants or transport fuel. These applications score just as high as the use in feed applications in the proposed system. Using fats as for heat scores lower. And wasting fat score 0.

Most agricultural residues and wastes are composed of many other components besides fibre, i.e. protein, fat, starch and sugars, nutrients (phosphate and potassium) and sometimes other relevant molecules such as latex or resins, etc. Apart from using each component preferably at the highest level first and efficiently, it is also important to understand that some components have a higher cost or value or are more scarce and non-renewable than others. For example, fat has an energy content of ~40 MJ/kg while fibre has an energy content of approximately 18 MJ/kg. This is important especially for feed and energy applications. In the case of protein, the energy value is roughly similar to carbohydrates, but it requires more energy (and pollution) to fix nitrogen and produce protein. Therefore, using protein efficiently is generally more important than using carbohydrates efficiently and turning protein into energy is a lower-level application then for carbohydrates. Nitrogen (the major constituent of protein) is important as a fertilizer. Similarly, the energy content of simple carbohydrates (sugars and starch) is roughly the same as that of fibre. Phosphate is a finite and scarce resource, as to a lesser extent, is potassium. It is therefore important that these elements are conserved and in the end are efficiently used as a fertilizer again. Following the reasoning above the relative importance of different residue components are presented in Table 3 where a simple point system indicates which component should especially be used more circular.

Table 3 *Example of a rating of importance of components for efficient use*

	Fibre	Protein (N = Protein/6.25)	Fat	Starch / Sugar	Phosphate	Potassium
Given value	+	+++	+++	+	+++++	+++

The hierarchy of applications for different components (Table 2) and the weighing system for the components (Table 3) should help in deciding which application of an agri-residue scores better with respect to circularity.

Of course, with regards to circularity and component importance, efficiency needs to be taken into account. An inefficient process that utilizes protein out of an agri-residue for human food may thus be less attractive than an efficient process that utilizes protein out of the same agri-residue for a lower scoring application. It becomes evident, that at this point prioritization may sway the outcome of individual circularity evaluations, depending which components and factors are in focus.

Circularity is a very important factor, but by far not the only factor to consider when it comes to evaluating alternative routes for the valorisation of agri-residues. Other factors such as socio-economic impact, environmental impact, and “implementability” also need to be considered. These domains are further described and defined in section 1. But first, a closer look at the history of agri-residue valorisation is given in the following sub-chapter, describing experience with solving pollution problems with agri-residues and the lessons that can be drawn from this.

4 Applying the circular valorisation tool to selected case studies

In the following sections four case studies from around the world are presented and the circular valorisation tool is applied to each case. Two of the four case studies show cases that have been implemented on large scale, for a third, the protein recovery from sugar beet leaves (section 0), is still at pilot scale. The benefit of hindsight facilitates answering some of the questions and scoring the indicators. More importantly, it enables understanding bottlenecks and challenges, that needed to be overcome in the implementation of the processes. In order to change existing processes into more efficient ones, these challenges need to be identified and addressed as early as possible. Each case has its own specific challenges, which were solved in even more unique manners. The overall approach to assessing the circular valorisation of agri-residues will be discussed in chapter 5, along with some of the lessons learned from the represented case studies. The following sections describe the situation before new processes were proposed and implemented and rate the changes in each criteria.

4.1 Nutrient recycling from household waste in Accra, Ghana

Rapid urbanisation in developing countries has intensified the challenge on management of waste flow (Drechsel, Cofie, and Danso 2010). Services such as sanitation are poor or inadequate to cope with growing rates of urbanisation and the associated higher standards of living (Cofie et al. 2006). In the years 2000 in Ghana, for example, 58% of the solid waste created was discharged by households in designated dumping sites, 25% was discarded in non-designated dumping sites and only 5% is collected. In general, the quantity that is not collected varies and can reach 20% in large cities such as Accra (Ghana Statistical Services 2002).

In 2012, The Accra Compost and Recycling Plant (ACARP) was formed. Ghana's first recycling and compost plant built by private financing, the first of its kind in the whole West Africa with a structure covering 120 acres of land. With the establishment of the plant, two challenges are covered in one blow: waste that threatens human and environmental health is removed and the farming community is helped with an affordable nutrient-rich organic fertiliser, which is used to improve the generally poor soil fertility of their lands.

The production of the organic fertiliser is claimed to offer multiple benefits, including new jobs, better human health, a cleaner environment and more nutritious diets, with less dependence on imported food and chemical fertiliser. As such, the project shows to positively contribute to all three (i.e., social, economic and environmental) sustainability dimensions of the food system. Following a description of the plant activity's contribution to the three dimensions.

Figure 5 Headquarters of the Accra Compost and Recycling Plant. Building from the outside (left) and internal reception (right). – source: maps.google.com

Circularity

The conversion of organic waste into organic fertiliser allows to enhance environmental protection by reducing waste quantities and the use of inorganic fertilisers in urban agriculture. Composting in Accra can be overall considered a useful circular practice as 85% of solid waste in Accra is organic material. On a yearly basis the estimated nutrient content in the waste is 3,500 to 5,300 tonnes per year, phosphorus 1,700 to 2,600 tonnes per year (Drechsel et al., 2010). The nutrients in the organic matter are partly re-used in agriculture via composting. In terms of land sparing, the increased yield expected by application of the organic fertiliser is expected to reduce the land requirement by producing more food on existing land. The utilization efficiency of converting household waste to compost/fertilizer is relatively high, but more modern composting techniques could be used to further improve efficiency.

Figure 6 Advert of the organic compost by ACARP (left) and organic waste (right). – source: acarpghana.com

Socio economic impact

The project has an important socio-economic impact in terms of job creation. The project also contributes with value added and rural development as local farmers have access to affordable organic fertilizer, thus positively contributing to the city's consumption needs as urban farming provides up to 90% of the city's consumption (Drechsel, Cofie, and Danso 2010). Moreover, the facility is also used by students as an opportunity to gain experience in the field. However, full value added is not reached as the compost plant does not produce other resourceful products such as biogas, that may furthermore boost the local economy.

In terms of profitability, there are difficulties in securing finances as the revenues from compost sale rarely cover processing, transportation and application costs (Hoornweg and Otten 1999). In effect, though, 200t of organic fertiliser are produced per day, it is worth specifying that the organic fertiliser sales contribute only 2% of the total revenue. This financial drawback is alleviated by the availability of incentives and subsidies from the government.

Figure 7 Key institutional networks representatives meeting with ACARP (left) and students visiting the facility (right) . – source: acarpghana.com

Environmental impact
Composting allows to reduce the overall quantity of waste left in the streets, drains or landfills that significantly contribute to environmental pollution. In effect, with composting pollution is mitigated as with other waste management activities such as landfilling, most waste contaminates the environment transforming cities into nutrient sinks (about 20% of nitrogen and phosphorus is lost in landfills (Drechsel et al., 2010).
First of all, GHG emissions are lowered compared to landfilling that produces methane more harmful than the carbon dioxide produced by composting. Moreover, soil quality is improved with the use of organic fertiliser due to its long-term soil reclamation properties such as: ability to reduce disease and pests, promotion of higher yields of agricultural crops, high presence of micro-organisms that contribute to break the organic matter into humus, ability to improve soil structure and shelf life, reduction of the loss of nutrients and improves soil tilth to permit better root growth (ACARP 2020).
Water quality is slightly improved as composting, in contrast to landfills, prevents components of the waste to drain into soil and possibly reach aquifers. The biodiversity of farms where the fertilizer will be used will moderately rise since the increased yield will require less expansion of land for agricultural reasons.

Figure 8 Application of the organic compost. - source acarpghana.com

Implementability
Firstly, to implement the project, there was the need to import technology and knowledge from European countries. However, the level of technology and knowledge required was not extremely complicated. Secondly, there was no need for additional infrastructure if not the building of the compost plant itself. The project helped in reducing the need of covering long distances with transportation. In fact, transportation costs have been reduced as the plant is decentralised and serves waste collection points with a distance of 5km at maximum, very positive compared to the 18km distances for taking waste to landfills.
The presence of a public-private partnership (business networks around the composting activity) highlights the positive side of implementability both from the input side and the output side. Private companies in Accra bring their waste to the compost plant, and real estate developers buy the compost, being interested in it for gardening purposes. Thirdly, for what concerns enabling policies, the Ghanaian Ministry of Local Government and Rural Development issued an Environmental Sanitation Policy in 1999 reviewed in 2010, that sought to promote waste minimization, reuse and recycling (Ministry of Local Government and Rural Development Ghana 2010). This shows that, the project did not require new policy formulation. However, there is a gap between waste management policy and actual waste management practices, especially at individuals and communities' level. For increasing the implementability of the project, the government had to put in place subsidies that were not present before, both for the fertilizer’s production and use (by farmers).

Overall, as a result of its positive impact on different indicators within the socio-economic and environmental aspects and on the relatively high implementability score, there is a local appreciation of composting activity. In effect, there are plans in place to build new plants all over Ghana and double the capacity of the ACARP compost plant in Accra to a total of 1200 tons of waste processed per day, also considering the fact that landfills are full.

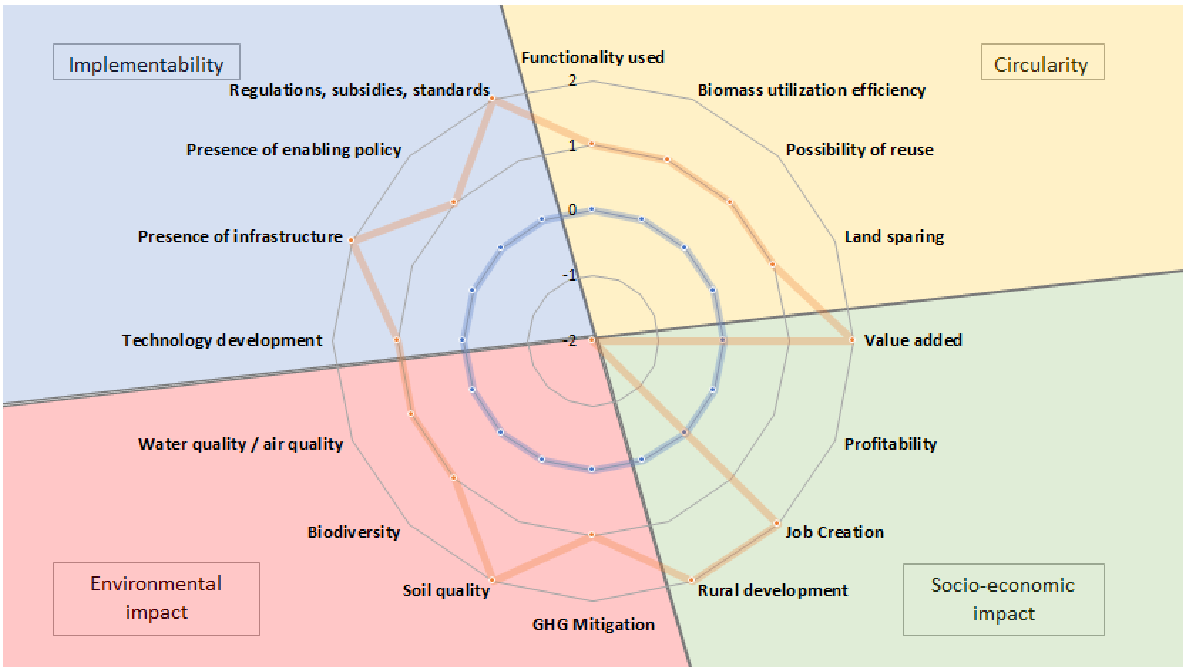

Figure 9 ***Visual assessment of nutrient recycling from household waste in Accra comparing original landfilling to producing compost from organic waste. For the original case the scoring is 0.***

Table 4 *Scoring of criteria and short explanation for assessment of nutrient recycling from household waste in Accra*

Domain	Category	Score	Description
Circularity	Functionality used	1	Using the nutrients in the compost matter for fertilizer purposes has higher functionality than using them for energy or burning.
	Biomass utilization efficiency	1	The biomass utilization efficiency of converting household waste to fertilizer is relatively high, but more modern techniques could be used to further improve efficiency.
	Possibility of reuse	1	The nutrients in the organic fertilizer can only be partly re-used and not in consumption.
	Land sparing	1	Less use of land required to produce more food as yield increases due to fertiliser.
Socio-economic impact	Value added	2	Farmers all over the country can have access to cheaper organic fertilizer (more revenue available from less costs of production).
	Profitability	-2	Difficulties in securing finances as the revenues from compost sale rarely cover processing, transportation and application costs. Organic fertiliser sales contribute only 2% of the total revenue.
	Job Creation	2	The local population is employed in the daily activities of the plant (65% of local population).
	Rural development	2	Farmers all over the country can have access to cheaper organic fertilizer (more revenue available from less costs of production).
Environmental impact	GHG Mitigation	1	Composting produces carbon dioxide that is less harmful than methane produced by landfilling.
	Soil quality	2	Application of organic fertiliser as multiple long-term soil properties.
	Biodiversity	1	Less use of land required to produce more food as yield increases due to fertiliser.
	Water quality / air quality	1	Composting produces less agri-residuals into the soil than landfilling.
Implementability	Technology development	1	The imported technology and knowledge from Europe was not extremely complicated.
	Presence of infrastructure	2	No need of infrastructure, rather reduction of use of available and non-available roads. Moreover, business networks have been strengthened.
	Presence of enabling policy	1	Enabling policies are already present, although implementation could be increased.
	Regulations, subsidies, standards	2	Subsidies have been put in place by the government both for fertiliser production and use by farmers.

4.2 Pineapple residues in Costa Rica

Costa Rica is the largest exporter of fresh pineapple to US and European markets with a growing production that reached a total of 44,500 hectares in 2017 (CANAPEP 2017) , an increase of 9000 hectares in just one year compared to 2016. This increase in production is accompanying by both economic benefits to the producing regions, but also environmental concerns (Ingwersen 2012).

Pineapple production presents difficult challenges. On the one hand, after a plant has been harvest twice, farmers have to remove the crop residues as soon as possible to replant. These crop residues if not disposed of quickly, serve as habitat of a stable fly that becomes a plague; and so the fly is strongly regulated by the government. Farmers manage the fly hazard by using herbicides, repeated ploughing or burying the residues in holes, sometimes together with microorganisms as accelerators of decomposition. Some of these techniques have long-term risks, with consequences for soil fertility, environmental pollution and the health of workers and the community surrounding the fields (Nennie and Boer 2018).

On the other hand, pineapple crop residues (estimated annual volume of 4.5 million) can serve on several valorisation options. For example, the University of Costa Rica reported on valuable characteristics of pineapple residues. Residues can be used for paper, construction materials, aliments, energy, plastic, and as a substrate for oyster mushrooms cultivation. (Nennie and Boer 2018). However, the challenge still is to find an application for all residues, since many applications only partially used some residues.

Methods of disposal include shredding incorporation, green burning and field compost under plastic. Other alternative scenarios include biogas for electricity, biogas for transport, thermal conversion and biorefinery plus biogas. In order to assess the circularity of this scenario, we analyse the pineapple case in Costa Rica from a baseline scenario of intensive used of herbicides, fire and shredding and compared to an alternative scenario of Biorefinery (fibre + enzyme) and production of biogas.

Circularity

Generating biogas from pineapple residues for electricity production would help to remove the biomass from the field solving the stable fly problem. Furthermore, it will have no costs for insecticides and herbicides and contribute to ease the environmental issues. Fewer nutrients are lost due to leaching, burning or disposal in a hole and a digestate produced by biogas installation has better nutrient value and can be applied when the crop needs it. Overall, it would have a positive effect on soil-borne diseases as removal of the biomass is a sanitary measure and less machinery passes required, would allow saving fuel and improve soil texture; While contributing to a carbon-neutral economy of Costa Rica. Although biorefinery has considerable potential still needs biogas or composting for residues processing. It requires the development of research on harvesting residues since currently, the focus is on pineapple tops and peels and cores.

Socio-economic impact

Generating biogas from pineapple residues for electricity production could save considerably on agrochemical costs and some fertilizer costs. Some of the most critical prevailing issues are related to social problems including low work stability, immigration from urban domains to cities, loss of crop diversity and therefore food security and dependency on supply companies. There are machinery costs to consider and large investment costs. Overall, costs and benefits for farmers are estimated to be positive including new sources of employment (Pia Gamboa 2014).

Environmental impact

A study conducted by EARTH University in Costa Rica highlighted that the most critical concerns of farmers include soil erosion, loss of inherent soil fertility, and reduced crop productivity, deforestation Poor residue management resulting in swarms of stomoxys calcitrans flies that attack cattle on large beef cattle farms and reduce weight gains, sedimentation and clogging of water basins and contamination and degradation of water resources by high use of pesticides (Pia Gamboa 2014).

Currently, there is evidence that pineapple production is affecting aquatic watershed and ecosystems, degrading riparian habitats and increasing pesticide levels in water (Echeverría-Sáenz et al. 2012) Converting pineapple residues into biogas for electricity could contribute to effective control of the flies while reducing significantly the dependency on the use of insecticides and herbicides. At the same time, it will improve nutrient recycling and avoid nutrient runoff/leaching.

Implementability

In Costa Rica, the government defined a long-term agricultural and rural development strategy, which place the agricultural sector as inclusive, modern, competitive and environmentally-responsible development (Ministerio de Agricultura y Ganaderia de Costa Rica (MAG) 2011). However, there are few guidelines to stimulate sustainable practices at pineapple producers. (Nennie and Boer 2018).
In order to convert pineapple residues into biogas for electricity, a market has to be created for residue products. Currently, biogas production is not practicable because it is not allowed storage electricity. Electricity from biogas needs to be sold to the Institute of Electricity of Costa Rica (ICE) at a low price. Nonetheless, there are plans to increase the electricity tariff generated by biomass, and the production of biogas also produces bio-fertilizers, which can be used to replace the current chemical fertilizers (Nennie and Boer 2018). Therefore, a successful application of biogas production is not in line with the current policies in place that prevent a profitable activity, consistent with a sole company of electricity distribution in Costa Rica.
Furthermore, not every pineapple farm is the same. There is significant variation between farms, which makes initiatives challenging to mechanise. Machinery is expensive and in general, investments are costly. Limited research has been conducted about the economic feasibility of residue valorisation options on-farm scale. Transport is expected to be expensive. Therefore it is essential to manage logistics well to decrease costs (Nennie and Boer 2018).
The following table complete the circularity tool from a baseline scenario of intensive used of herbicides, fire and shredding and compared to an alternative scenario of Biorefinery (fibre + enzyme) and production of biogas. Expert advice is gathered from Elbersen and Hengsdijk (Hengsdijk, H., & Elbersen 2019) presentation of the results of a fact-finding mission on Costa Rica’s pineapple residue valorisation (annex 0).

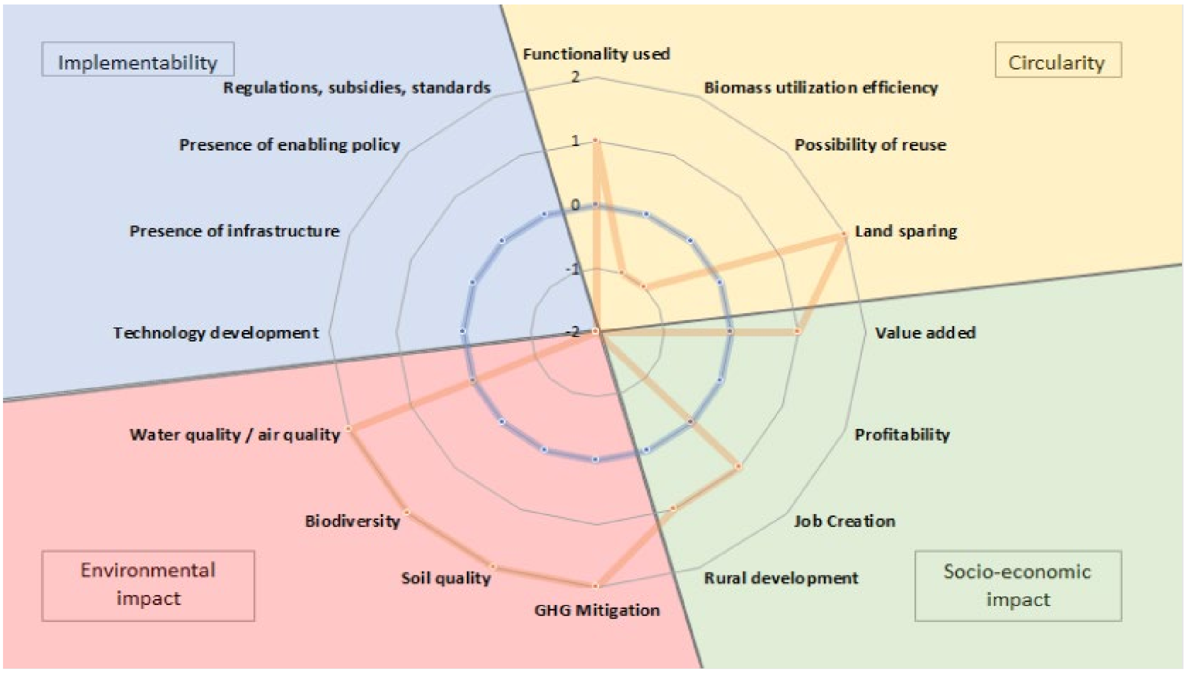

Figure 10 Visual assessment of pineapple residues.

Table 5 ***Scoring of criteria and a short explanation for assessment of pineapple residues in Costa Rica***

Domain	Category	Score	Description
Circularity	Functionality used	1	Used for sustainable energy
	Biomass utilization efficiency	-1	Requires the development of research on harvesting residues, since currently, the focus is on pineapple tops and peels and cores.
	Possibility of reuse	-1	Not all residues are used.
	Land sparing	2	Cycle length and biomass used. Less land can be used for the same amount of pineapple by replanting earlier.
Socio-economic impact	Value added	1	Biofuel can be produced. Benefits for farmers are estimated to be positive
	Profitability	-2	Converting pineapple residues into biogas for electricity could save considerably on agrochemical costs and some fertilizer costs, but there are machinery costs to consider and large investment costs
	Job Creation	1	It can include new sources of employment
	Rural development	1	Could contribute to rural development if research and infrastructure are implemented
Environmental impact	GHG Mitigation	2	Biogas would promote fossil fuel mitigation
	Soil quality	2	Promote soil quality with less use of herbicides and insecticides. Nutrient recycling, nutrient runoff/leaching and organic matter.
	Biodiversity	2	Promote biodiversity in the soil with less use of herbicides and insecticides
	Water quality / air quality	2	Promote water quality with less use of herbicides and insecticides. Also, promote air quality with less burning of residues.
Implementability	Technology development	-2	Limited research has been conducted about the economic feasibility of residue valorisation options on-farm scale.
	Presence of infrastructure	-2	There is significant variation between farms, which makes initiatives challenging to mechanise. Transport is expected to be expensive.
	Presence of enabling policy	-2	Biogas production is not practicable because it is not allowed storage electricity.
	Regulations, subsidies, standards	-2	Electricity from biogas needs to be sold to the Institute of Electricity of Costa Rica (ICE) at a low price.

4.3 Recovery of protein from sugar beet leaves in the Netherlands[1]

Royal Cosun has turned sugar beet leaves, which were traditionally left on the field after harvest, into sources of functional food grade protein. Royal Cosun is a cooperative sugar producer, that has nearly 120 years of company history. With the advent of modern harvesting machines, sugar beets were immediately separated from the leaves, after being pulled from the ground. While the sugar beets were collected and brought to the factory for sugar production, the leaves were left on the field to rot. With the advent of new technologies, a new business case was made: recovery the water soluble protein fraction out of the leaves. It is currently run in pilot scale and scaling up is planned.

The main reason for developing the new process was economic: added value from existing streams, which lead to a more robust agro-system. The main driver for the transition was protein demand: the extracted protein is highly functional, for example as chicken-egg protein replacement. Based on this demand a convincing business case was made, which led throughout the decision making process.
It was not policy at the time, that incentivised the push, but purely economic reasoning. On the contrary, policy limiting fertilization actually makes the business case less attractive, as nutrients which used to be returned to the soil in the form of rotting leaves, were now not fully replaceable.
The entire operation, including the built of the pilot plant were privately funded through corporate interest.

Sugar beet is a typical agricultural plant grown around the world in temperate climates. Its root contains high concentration of sucrose, which is refined into sugar in industrial processes. World production reached 277 million tonnes in 2016. Harvest machines immediately separate leaves from root and collect the roots for processing, while the leaves were traditionally tossed back on the field to rot after sugar beet harvest.

The leaves contain a significant amount of protein, which is wasted on a large scale given the mass of leaves produced annually. Shifting interests and improvement in process technology (driven by this case) led to economically feasible recovery of leaf protein. Royal Cosun is running protein production from sugar beet leaves, Rubisco, on a large pilot scale facility in the Netherlands.

While this presents an interesting turn in regards to circular economy, it leaves the sugar beet farmers with a real loss of nutrients in their soil. The leaves, that used to decompose on the fields, are now removed. This loss is, apparently, legally not recoverable through fertilization, leaving a real loss to the fields nutrient levels. Therefore, the new process yields a new source of food grade protein, which scores high in terms of circular economy, but it leads to soil depletion, a rather unsustainable act.

In light of this twist, in part generated through policy (fertilization statues), food protein production from sugar beet leaves forms an interesting case to be evaluated for its role in a circular economy.

Circularity
In terms of circularity, the new process scores very high as the full functionality of the proteins are used. However, the process is not very efficient, as not all the protein in the residual stream is recovered, this is still much better than using none at all though. The residual stream, after protein extraction, is pressed and used as cattle feed, still a highly functional application. This newly established source of protein leads to indirect land sparing, as elsewhere less land is required to produce protein.

Socio economic impact
The socio-economic impact is limited in terms of job creation and rural development. The process is however highly profitable, profit was the driver of the entire process development, and the added value, from waste to functional food protein, is very high.

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[1] This review is partially based on an interview with Paulus Kosters of Cosun

Environmental impact

The environmental impact is improved through reduced greenhouse gas emission and possibly increased bio-diversity (in traditional protein or feed producing countries), again indirectly by requiring less traditional protein production. Soil quality is actually degraded as nutrients cannot be replenished in full through NL/EU legislation.

Implementability

Implementability was hindered by aforementioned legislation that reduces fertilization possibilities. It did not stop the process, but also did not help. Technology and knowledge were pretty much in place beforehand, but some dots had to be connected. Infrastructure will become important in the coming phase of scaling up from the pilot plant. While there were no governmental subsidies, EU innovation grands were given after the pilot started running successfully.
As far as technology development was concerned, at the time the process was designed it was more a matter of applying existing technologies to the process, rather than development of new technologies.

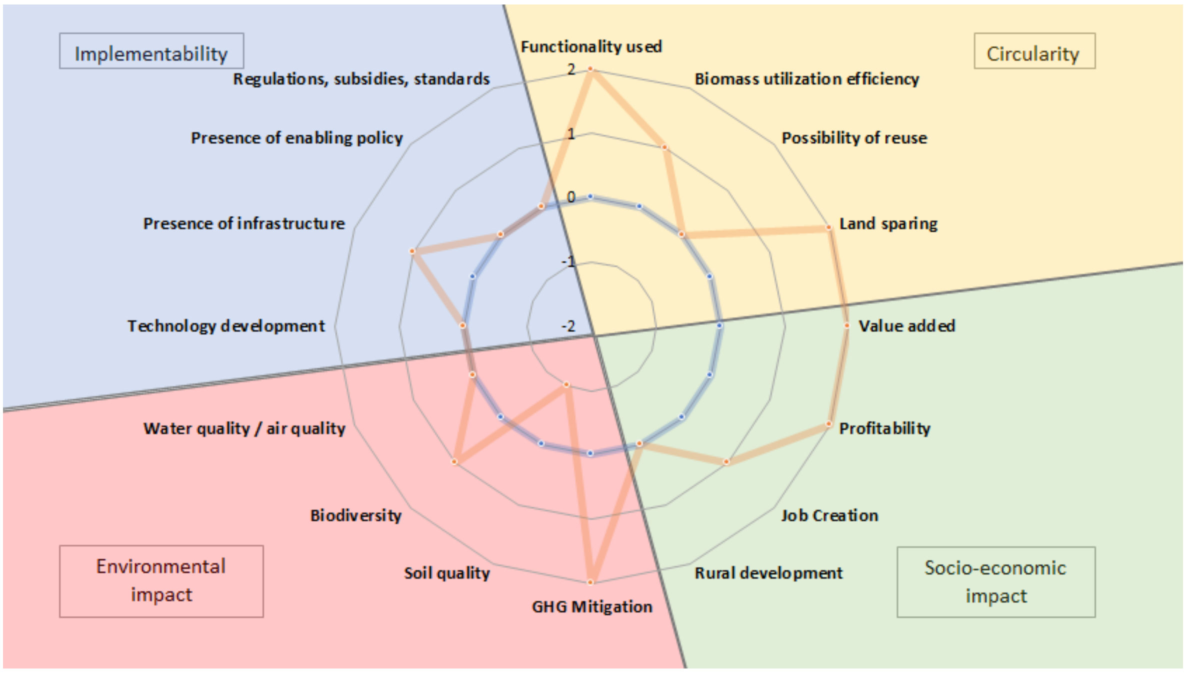

Figure 11 *Visual assessment of protein recovery from sugar beet leaves.*

Table 6 ***Scoring of criteria and short explanation for assessment of protein recovery from sugar beet leaves.***

Domain	Category	Score	Description
Circularity	Functionality used	2	Protein functionality at highest level. Specialty food applications. Cannot do better.
	Biomass utilization efficiency	1	Efficiency of the process can still be improved. Process has been improved already.
	Possibility of reuse	0	Food protein is consumed. No reuse of protein.
	Land sparing	2	Land saved for alternative protein production, e.g. egg or soy protein production
Socio-economic impact	Value added	2	Food protein is a valuable product
	Profitability	2	Most likely positive, efficiency not optimal yet
	Job Creation	1	Few people involved in running the factory
	Rural development	0	Not negative, but also not huge effect.
Environmental impact	GHG Mitigation	1	Reduced GHG due to less egg or soy protein production. Less nitrogen and GHG release due to decay in winter. Efficiency of process still limited.
	Soil quality	-1	Part of the nutrients are removed from the field. Due to regulations nutrients cannot be replaced in full.
	Biodiversity	2	Less land required, indirect positive biodiversity effect. Direct effect should be limited.
	Water quality / air quality	2	Removal of crop residues from fields helps reduce contamination of water streams. Especially on sandy soils.
Implementability	Technology development	-2	From the standpoint of 10 years ago, technology development was needed (bottleneck). Today that technology is in place. Making a business case from the use of protein of this material was an obstacle, which led to the development of extraction and decolourisation methods while preserving the function.
	Presence of infrastructure	2	Infrastructure was in place all along
	Presence of enabling policy	2	Policy stimulating reduction of protein import and using local produce. Wish to reduce emissions into water streams.
	Regulations, subsidies, standards	-2	Nutrient removal is problem for farmers because policies deny total nutrient replacement.

4.4 Recovery of protein from starch production side streams in the Netherlands

Avebe, producer of potato starch, has turned its waste stream, potato juice, from an environmental pollutant into a valuable functional product: food grade protein. In the production of potato starch large quantities of potato juice (the liquid inside fresh potatoes) are produced. With the beginning of industrial production in the 19th century, this potato juice was just released into the canals, causing large scale environmental problem and leading to the entire north of the Netherlands to be infamous for its stench (Grommers and van der Krogt 2009). For scale: the two operational modern factories process around 250 t of potatoes per hour (during the half year production season), which leads to around 200 t of potato juice per hour containing 3% protein.

It was not until the 1970's that the protein was finally recovered from the agricultural residue, leading to a reduced environmental burden and extra products for sale: potato protein of different qualities.

Regulations were imposed by government, with policy pushing for a change in meeting environmental standards and the construction of new factories, after market shifts and factory consolidation in western Europe, finally led to the incorporation of protein recovery. According to J. Sanders, a large part of this change was financed by the government. In that time, European governments began to implement policies that reflected the growing awareness of planetary boundaries, e.g. in terms of limited availability of nitrogen and phosphor. These policies ultimately led to change, pushed for by governments. From company side, evident steps of coping with the residue problem are ignoring, leaving the problem for the next generation to solve, and then transforming the residue into a valuable product, leading to an improved process with a clean environmental footprint (as far as protein discharge is concerned).

Circularity
In all categories of circularity, the recovery of proteins leads to high or very high scores. The recovery of protein indirectly leads to land sparring and greenhouse gas mitigation, as feed protein production capacities elsewhere are less. Though the a large fraction of the protein is denatured in the process, it can be used for feed applications. Recovery of functional food protein comprises only on a rather small fraction of the total protein and requires higher processing costs. The possibility of re-use is relevant when used for feed as is it is partially converted to food protein and the remainder into manure for soil applications.

Socio-economic impact
The socio-economic impact of the transition described here is moderate. The main contribution is the reduced burden on the environment and thus improved life quality for the population of the area. Both in terms of profitability and added value the implemented process is an improvement from the status prior, albeit within limits, as the process is expensive in comparison to the majority of the product. Job creation and rural development are probably not impacted by the new process.

Environmental impact
The environmental impact of the new process is clear. Air and water quality were improved by the new process and green-house gas mitigation takes place, as conventional production of food and feed protein can be reduced elsewhere. The impact on biodiversity and soil quality are not known.
In the domain of implementability, the key factors were implemented, that enabled the change in processing. Government subsidies were tied to the condition of no longer discharging protein into the canals. This was in line with enabling policies regarding reduction of environmental impact. Conditional subsidies were probably the key factor that overcame the capital intensity required to develop and start the process. While the infrastructure was pretty much in place from the starch processing, the required technology needed to be developed and Avebe holds the key patents to the process.

Implementability

The implemented processes were not developed at the time and required R&D by Avebe. There are three main processes that lead to protein reduction in the waste water: adsorption (functional protein), heat coagulation (food grade product) and water evaporation (feed grade product). Therefore the used functionality is good, but not very good, as not all protein maintains its full functionality, a large part is coagulated for feed. The process is very efficient though, the vast majority of protein is captured. The remaining water is called *protoamylasse*, and after further water removal is sold as fertilizer (high K^+ content).

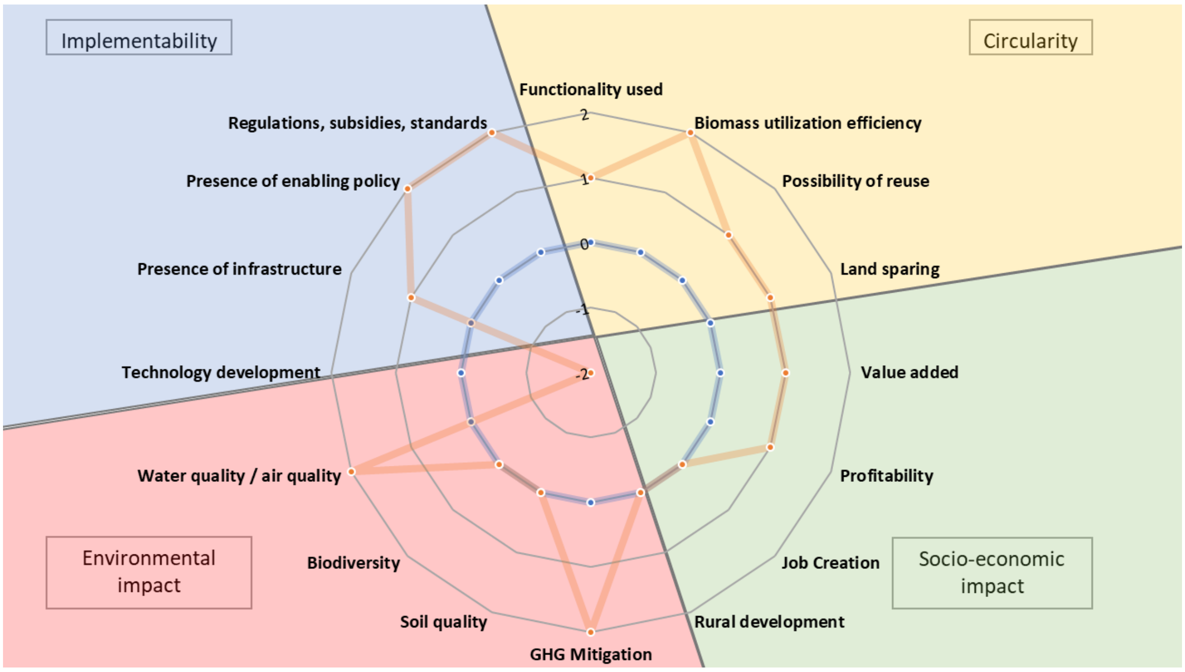

Figure 12 Visual assessment of protein recovery from starch side streams

Table 7 Scoring of criteria and short explanation for assessment of protein recovery from starch side streams

Domain	Category	Score	Description
Circularity	Functionality used	1	Not highest level. The bulk of the protein is heat precipitated, leaving feed quality protein. Only a small fraction is separated while maintaining functionality
	Biomass utilization efficiency	2	High, little protein is not captured
	Possibility of reuse	1	Remaining water is called protamylasse which is used as Kalium fertilizer for the field.
	Land sparing	1	Land that is required to produce protein is sparred
Socio-economic impact	Value added	1	Yes, within limits. Not all protein is functional
	Profitability	1	Yes, within limits
	Job Creation	0	Modestly at best
	Rural development	0	Modestly at best
Environmental impact	GHG Mitigation	2	Protein production elsewhere is reduced
	Soil quality	0	Not relevant
	Biodiversity	0	Not relevant
	Water quality / air quality	2	Major improvement in air and water
Implementability	Technology development	-2	Technology development was required. Avebe developed and holds the patents
	Presence of infrastructure	1	Factories were consolidated anyways, infrastructure was more or less in place
	Presence of enabling policy	2	Government stimuli and threats required to get the transition moving
	Regulations, subsidies, standards	2	Government subsidy required with attached condition of solving the environmental issues

5 Implementing alternative more circular agro-residue projects

Agri-residues are usually by-products of long established processes (farming or processing agricultural products). With increasing scale and industrial growth, these by-products turn from a nuisance to problem. At the same time, with technological improvement and economic possibilities, agri-residues can be valorised in new ways.
It has been shown that the process of improved valorisation is often a long one, evolving in steps rather than leaps and often requires outside nudges for implementation (See annex 9.1). For example, the smell of Frisian waters due to discharged protein in waste water was not seen as a problem for a long time. And when it was finally recognized as a problem, it took years to government incentives to solve the issue.
The implementation of circular agro-residue valorisation does not follow a clear pattern. Certain pathways address environmental problems (e.g. protein containing residue discharged into waterways or harvest residues for a pest breeding ground) or provide an economic opportunity (protein recovery from crop residues).
As the cases (presented in the previous chapter and in annex 9.1) show, addressing an environmental problem, requires pressure and threats and but also incentives (from the government). In case of the household waste recycling and protein from sugar beet, economic incentive was the main driver to implement the new process.

When a better and more sustainable and potentially profitable alternative use for an agri-residue is found often major bottlenecks are found in the domain of implementation. Changes in regulations, laws, or policies may be required to make an alternative application of an agri-residue possible. In many countries, electricity generated from biogas generated from crop residues cannot be sold to the grid for a reasonable price. Such hurdles make it impossible to invest in bio-digestion facilities that may provide an alternative to using a crop-residue in a more sustainable way.

At the start of the evaluation stands the analysis of the status quo and the consequences of proposed alternative processes. Ultimately, the aim of the improved process should be the transformation of agri-residue in an optimal circular fashion. The first step is a clear definition of the problem and the identification of one or more possible solutions. In a second step the alternative uses of agri-residues should be assessed systematically to know if the alternative is viable. In a third step, obstacles have to be defined. Often these obstacles are found in the domain of implementability. Rules and regulation may have to be adapted or new knowledge or technology may have to be developed. This was the case for bringing potato waste streams and sugar beet leaves to value. Both, technological advancement as well as implementing the process, may be challenged by adequate financing, especially when new technologies are involved.

5.1 Decision tree

In this chapter a decision tree is presented that can be followed when evaluating and implementing alternative valorisation routes for agri-residues:

- Is there a problem or an opportunity that requires an alternative application or processing of an agri-residue?
- If yes, a potential solution has to be defined and compared to the current application of the agri-residue

For the comparison the factors to be included need to be decided on. Factors to be included can be varied from the base case discussed in Chapter 2, of course including the circularity scores, depending on the case at hand, local conditions or prioritization. Next, data required for evaluation needs to be collected and inserted into the multicriteria analysis.

When the analysis is done, the resulting scores are evaluated for the satisfaction of the output. If the resulting overall score is not satisfying, an alternative or improved process or application needs to be identified (back to top).
If the results of the multicriteria analysis are satisfying, then issues that may hinder implementation need to be analysed. Special focus is laid on technical knowledge, financial aspects, regulation, and policy as well as infrastructure (for detailed description, see section 2.4). If the issues are solved, just as if no implementation issues are identified, the new solution can be implemented.

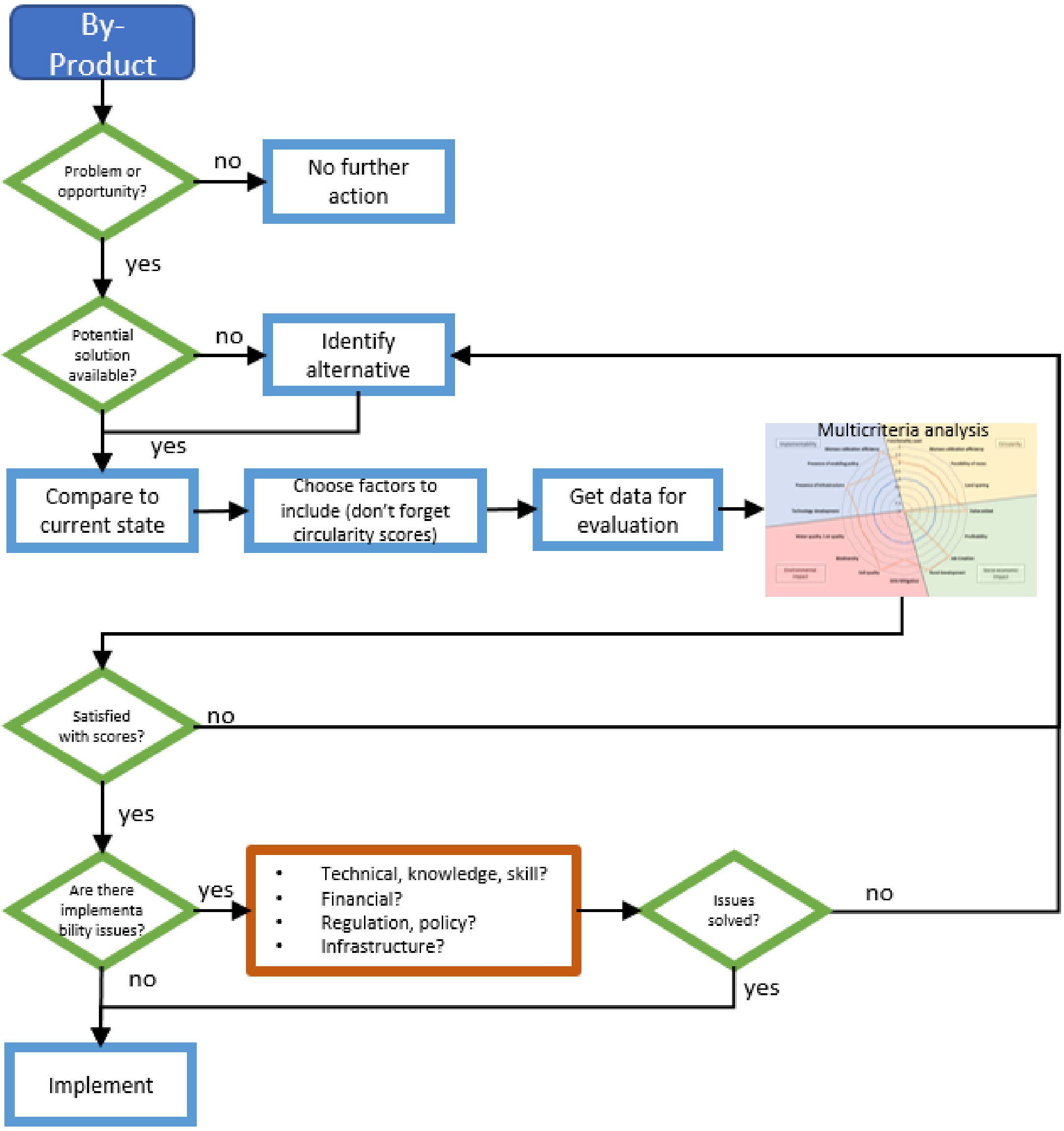

Figure 13 ***Decision tree for circularity evaluation***

6 Concluding Remarks

In agriculture many residues are produced in the field or during processing. Too often these residues cause environmental problems when being discarded or improperly disposed. In almost all cases, value can be generated from the residue streams if proper processes are applied. As seen in the case studies, environmental problems alone are usually insufficient to bring about change. Even in combination with financial incentives, change is not necessarily imminent, but further incentives may be required. In the case study of protein discharge from potato starch industry, the final incentives were often brought about by government threats of withholding funding.

However, before processes are changed and new strategies implemented, it is important to understand the consequences and maximise potential positive effects of alternative processes. For the comparison of the current state with new proposals, this report adds a new dimension in the criteria that are used to evaluate processes: circularity quantification. With the aim of promoting a circular economy, the actual circularity of different processes must be expressed in a form that allows quantitative comparison. The here introduced dimension allows that. By establishing a logical hierarchy of by-products and their main components, the groundwork is laid out for a scoring based system that allows process comparison based on a variety of (flexible) criteria.

The set of tools described in this report were engineered with the aim to help agricultural counsellors make decisions in the evaluation of circularity. Other, currently ongoing, projects are working on the evaluation of circularity with greater attention to detail and depth. This report aims at delivering a relatively simple to implement tool that yields comparative data relatively fast. Logical steps are followed in the execution and a set of questions must be asked and answered. With this tool identification and understanding of bottlenecks in implementation can be identified at an early stage.

In the authors’ opinion, agricultural counsellors have a lot of tools at their disposal to help implementation. It is hoped the proposed system helps identify what is worth pursuing.

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Annex 1 Lessons from the history of agri-residue valorisation

The evolution of waste treatment often takes decades and many different steps until finally solutions are sought in adding value to the residue, thereby turning a waste into a co-product. Sanders identified eight steps in which waste problems were typically dealt with (Sanders, 1993). The steps are: Ignore, Hide, Wait, Cure, Dilute, Transform, Prevent, and Improve. Of course, it is best to prevent a waste from occurring or using the waste for "improved" applications. However human nature apparently dictates that a longer process of several steps is followed while dealing with agri-residue. The notion of the eight steps can be used to define the problem itself and its possible solution but also describe how problems are dealt with in time.
In effect, this helps in understanding the circularity potential of a project by identifying how much value can be added (or if any value can be added at all) to agri-residues in the different stages.

According to Sanders the most widely practiced attitude towards waste management are to ignore and to hide the problem. These two steps contribute to the waste problem as they do not even allow to understand whether the agri-residues or components of it could potentially be turned into something of economic value. At first, these two steps are often accompanied by denial of scope and actuality of the issues at hand. Additionally, just like the next step, they leave the problem to be dealt with for future generations. An example is plastic pollution that for years has been an environmental problem mostly ignored.

The following step is to wait, that is described as a way to elaborate on an affordable solution for the problem. In this phase, research can play a role in defining the potential of the agri-residues contained in the waste in terms of circularity. Also, adaptation of policy can help reduce the waiting period. Cure does not deal with the source of the problem, but attempts reduce the impact of the residues, often at great cost. Therefore, this step does not pose attractive long-term solutions. A fitting example would be the construction of a higher smokestack, to reduce air pollution in adjacent areas, without actually reducing the exhaust of pollutant.
Another way of coping with waste is to dilute and it happens mostly in circumstances where the environment is capable of recycling the level of waste offered. At this level as well no intentional re-use of residues is applied, rather nature is left deals with it. An example is to let liquid waste from factories go into aquatic ecosystems, that have a capacity to absorb and degrade a certain amount of pollutants, with the idea that adding water decreases the concentration of the pollutant.

The three lasts steps of Sander's way of coping with waste problems are considered the only ones to be applied in the contest of sustainable agriculture, thus should be alternatives to be considered in case of recycling projects. In effect, firstly, to transform allows to cope with environmental needs and preventing creation of waste elsewhere by manufacturing a product. To turn household waste into organic fertiliser is a clear example of reducing or eliminating a waste problem and adding value by creating a new product that can be used within the supply chain as input. Secondly, to prevent creates a clean environment with the drawback of having high production cost. An example from the hospitality sector involving prevention of food waste is to avoid buffet style service and prioritize "a la carte", or to target the usually wasted food products and dishes (e.g. fruits, vegetables, rice, noodles and cakes) by improving food preparation techniques (Papargyropoulou, E. Lozano, R. Steinberger, J.K. Wright, N. & bin Ujang 2014). Thirdly, to improve would mean to have a clean environment (as in prevention), but with the addition of having improved products and/or processes. This is the desirable step and the one that mostly would be able to represent sustainability in its three dimensions (environmental, social and economic). Though "to improve" is mostly related to niches in innovation within the food system, there are currently companies making use of improved processes and products. For example, Goodhout, a company that produces coconut husk composite material used for all sorts of products (for interior design elements, fashion or furniture accessories) from 100% postharvest coconut waste.

The process is improved using a technology that activates the naturally present glues in the coconut husk to produce the bio-material (GoodHout 2021). These steps are needed to ensure a sustainable food system, but they also require considerable investments.

Annex 2 Comparison of impacts of two options for dealing with pineapple residues. Refer to section 4.2 on pineapple residues in Costa Rica

Assessment criteria	Herbicides / fire /shredding	Biorefinery + biogas
1. Control fly		
Effectiveness of control	1	2
Use of insecticides	-2	2
Use of herbicides	-2	2
2 Disease control	1	2
3. Soil effects		
Nutrient recycling	-1	2
Nutrient runoff/leaching	-1	2
Organic matter	-1	2
4. land use efficiency		
Cycle length	0	2
Biomass use	-2	2
5. Potential GHG saving		
Fossil fuel mitigation	-2	2
Methane emission	0	2
6. Costs and potential added value		
Agro-chemical costs	-2	2
Fertilizer costs	-1	0
Machinery costs	-1	-1
Investment costs	2	-2
Costs/benefits for farmer	-2	1
7. Policy/legal interventions		
In line with regulations?	-1	-2
In line with policy wishes?	-2	2
Policy adaptation needed	2	-1
Added value for society	-2	2
8. Employment effects	0	2
9. Research & Development		
State of development	2	-1
Research investment need	2	-2
Total score	-12	22

Source: (Hengsdijk, H., & Elbersen 2019)

Annex 3 Flyer on the process to find alternative circular applications for agri-residues via the circular evaluation framework

Quick guide to using the circular evaluation framework

Intro
Using agri-residues in a maximal circular approach requires a detailed assessment and comparison of current practice and proposed approaches. For the evaluation of alternative applications, a multicriteria evaluation tool based on component hierarchy and circularity quantification is proposed. Scores are designated to categories, which are situated in four main domains (Table A). Th scores range from -2 (worst) to +2 (best). The categories are flexible and can be adjusted based on situational requirements. Along with the scores a short description can be added to the table, to explain the given score.

Comparison analysis
First, an opportunity or a problem with an agri-residue is identified. Alternative applications or processes are analysed to apply the agr-residue. The decision process is detailed in Figure A.

For the existing process and proposed alternatives data is gathered to evaluate four categoric questions in each of the four different domains (Table A). Each category is scored on a scale from -2 to +2, relative to the current process. Next the alternatives are evaluated using the multicriteria analysis tool provided (Figure B).

Circularity and component hierarchy
With the aim of enabling circularity comparison, different alternatives are evaluated for their circularity, making use of component and by-product hierarchy. The use of functionality within the selected by-products ranks high. Generally, use for food application ranks highest, then feed, then materials such as chemicals and transport fuels, then energy, then burning without use of energy or landfill.

Assessment
The resulting multicomponent analysis figures are compared and evaluated for their potential impact and implementation issues. Local conditions and case priorities may sway decision making processes towards one or other alternative.

Table A – List of factors in four domains for assessment of impact and implementability of alternative agri-residues applications. Relevance of factors may differ according to case specific considerations.

Domain	Factor	Score	Description
Circularity	*Functionality used*	*From -2 to +2*	*i.e. Functionality used entirely, could not be better*
	Biomass utilization efficiency		
	Possibility of reuse		
	Land sparing		
Socio-economic impact	*Value added*		
	Profitability		
	Job Creation		
	Rural development		
Environmental impact	*GHG Mitigation*		
	Soil quality		
	Biodiversity		
	Water quality / air quality		
Implementability	*Technology development*		
	Presence of infrastructure		
	Presence of enabling policy		
	Regulations, subsidies, standards		

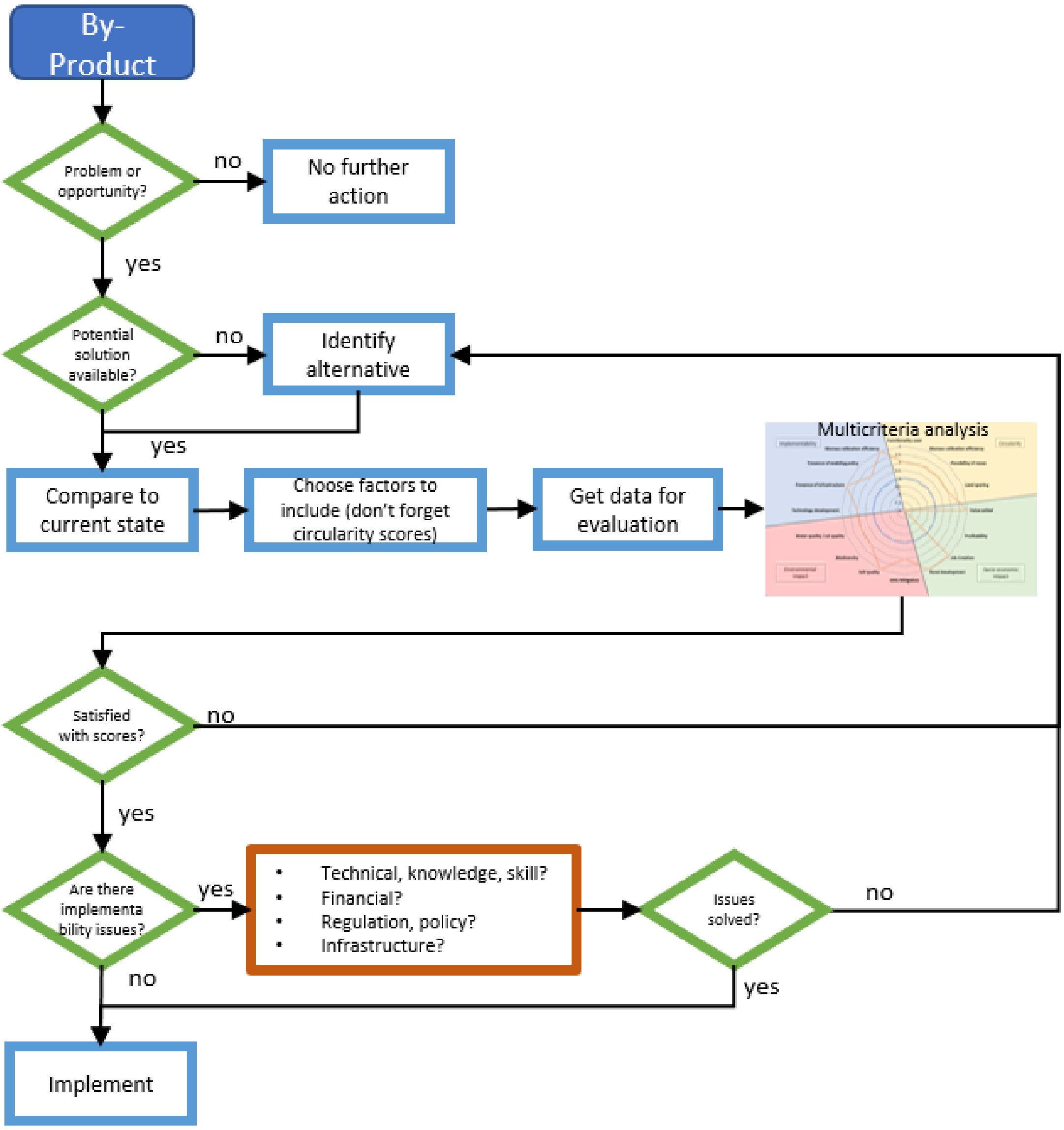

Figure A – Decision tree for circularity analysis.

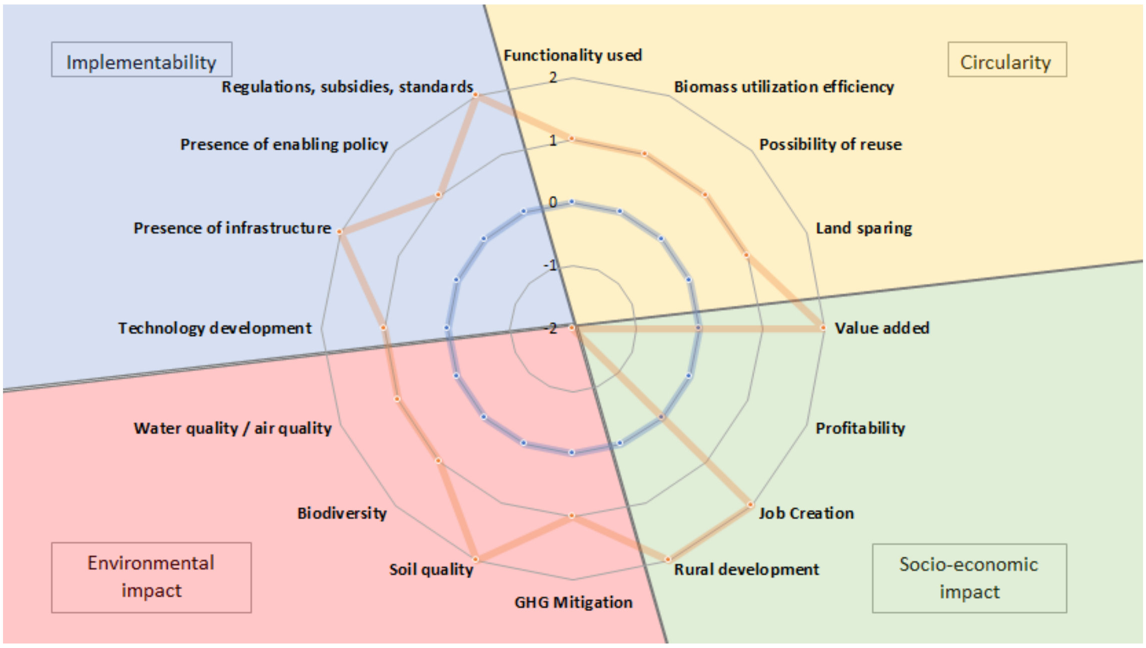

Figure B – Spider diagram showing the multicomponent analysis tool.

To explore
the potential
of nature to
improve the
quality of life

Wageningen Food & Biobased Research
Bornse Weilanden 9
6708 WG Wageningen
The Netherlands
E info.wfbr@wur.nl
wur.nl/wfbr

Report 2247

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