National Institute for Public Health
and the Environment
Ministry of Health, Welfare and Sport

Assessing sustainability of residual biomass applications

Finding the optimal solution for a circular economy

RIVM Report 2016-0135
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Colophon

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Synopsis

Assessing circularity of residual biomass applications
Finding the optimal solution for a circular economy

Various activities are underway for making new products from organic waste materials in order to minimise the quantity of materials that are wasted (circular economy). For example, the fertiliser struvite is being extracted from wastewater, and energy and fertilisers from cow dung or from beet pulp. New technologies are also increasingly making such developments possible. In order to facilitate sustainable and safe recycling processes, the Ministry of Infrastructure and the Environment (I&M) wishes to obtain insight into which of such activities it can encourage and which not. In order to decide on this, the National Institute for Public Health and the Environment (RIVM) has made an inventory of which information is needed to do so.

The RIVM finds it important to consider the impact of recycling on the environment from an integrated and broad perspective. Such an approach makes it clear what the consequences of a product are, from a social (human perception/experience, employment), financial, and environmental perspective. This avoids scenarios in which a recycling activity may be beneficial from the perspective of one production chain but damaging from the perspective of another.

For example, recycling processes should take into account that certain nutrients must remain behind in the soil to ensure that the soil remains healthy and can continue to fulfil its function. Situations must also be avoided in which a recycled product is no longer available for its original use and an alternative needs to be imported. For example, the consequence of recycling frying fat for use as biofuel is that there is no longer enough available for making soap and that palm oil needs to be imported for that purpose.

To ensure that organic waste materials are optimally recycled, it's advisable to properly weigh the impact of different alternatives and choices. To do so, a clear step-by step plan is needed that makes it possible to measure the consequences from a broad perspective. The RIVM is therefore a proponent of developing a standard method to do so.

Keywords: circular economy, residual biomass, resource efficiency, sustainability indicators, waste

Publiekssamenvatting

Methoden om de duurzaamheid van hergebruik van organisch afval te meten.

Aandacht voor de impact op het milieu

Er zijn meerdere activiteiten gaande om van organisch afval nieuwe producten te maken, zodat zo min mogelijk stoffen verloren gaan (circulaire economie). Zo wordt uit afvalwater de meststof struviet gehaald en uit koeienmest en bietenpulp, energie en meststoffen. Nieuwe technologieën maken deze ontwikkelingen ook steeds beter mogelijk. Om duurzaam en veilig hergebruik mogelijk te maken wil het ministerie van Infrastructuur en Milieu (IenM) inzicht krijgen welke van dergelijke activiteiten ze kunnen bevorderen en welke juist niet. Om hierover te kunnen beslissen heeft het RIVM in kaart gebracht welke informatie daarvoor nodig is.

Het RIVM vindt het van belang dat met een integrale, 'brede blik' wordt gekeken naar de gevolgen van hergebruik voor het milieu. Op die manier wordt duidelijk wat een product opbrengt, zowel sociaal (beleving, werkgelegenheid), financieel, als voor het milieu. Daarmee wordt voorkomen dat het hergebruik goed is voor de ene productieketen, maar schadelijk voor een andere.

Zo moet er bij hergebruik rekening mee worden gehouden dat bepaalde voedingsstoffen in de bodem achterblijven, zodat deze gezond blijft en zijn vruchtbaarheid behoudt. Ook moet worden voorkomen dat een hergebruikte stof niet meer voor zijn oorspronkelijke bestemming beschikbaar is en een alternatief moet worden geïmporteerd. Zo heeft hergebruik van frituurvet voor biologische brandstof tot gevolg dat er niet voldoende is om zeep van te maken en moet daarvoor palmolie worden aangevoerd.

Voor een optimaal hergebruik van organisch afval is het wenselijk de impact van keuzes goed te kunnen wegen. Hiervoor is een duidelijk stappenplan nodig dat het mogelijk maakt om met een brede blik de gevolgen te meten. Het RIVM pleit er dan ook voor om hiervoor een standaardmethode te ontwikkelen.

Kernwoorden: cascadering, circulaire economie, biotische reststromen, grondstof, LCA, duurzaamheidsindicatoren, afval

Contents

Summary

Residual biomass flows play an important role in the transition from a linear to a circular economy. Many residual biomass flows are already in use – in various applications, from soil fertilizer production to energy generation. Although these have the advantage of minimizing the waste of biomass, the optimization of residual flows in terms of sustainability remains a challenge.

For an optimal transition to a circular economy it is necessary to take sustainability and safety into account – in other words, to preserve the natural capital and develop novel applications for residual flows without creating unacceptable risks for people and the environment.

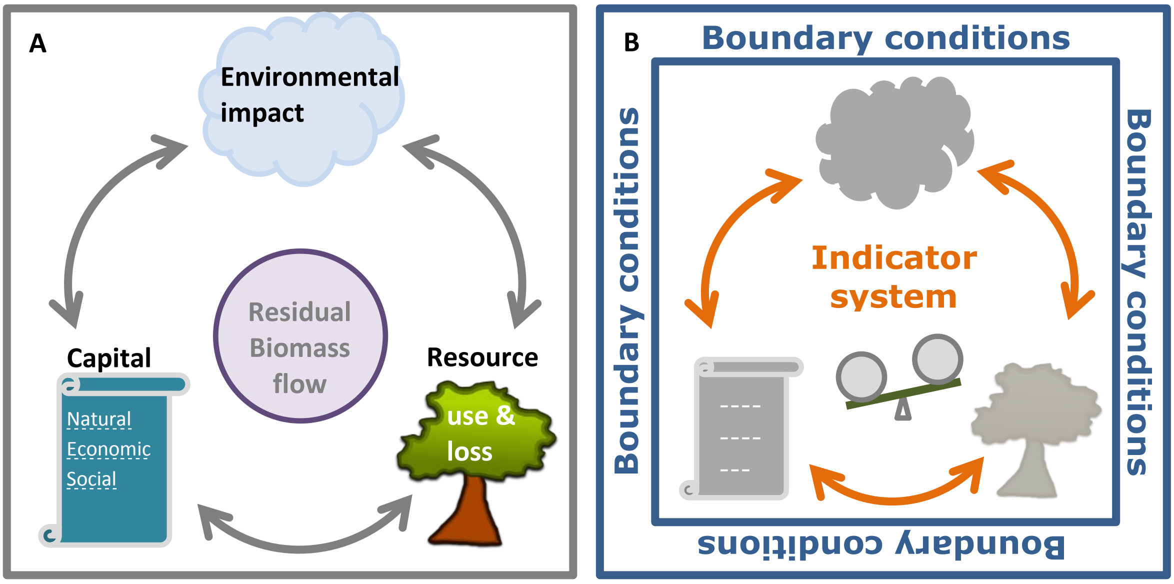
The aims of the current study are, first, to make an inventory of the issues related to the optimization of residual biomass flows; second, to review the existing indicators and methods for assessing their environmental impact and sustainability, with a focus on increasing resource efficiency and circularity; and third, to analyze these findings and report conclusions and recommendations.

Although there are many issues that play a role in optimizing the use of residual biomass flows, it is clear that the increasing purity of these flows makes higher-value applications possible. For this reason, the different processing steps that affect purity need to be considered. For example, the methods used to purify wastewater can also produce the phosphate mineral struvite. Although there are still several unanswered questions regarding the potential presence of pathogens and contaminants in such a residual flow, it has far greater potential for high-quality applications than the original residual biomass flows: effluent and sludge.

The use of a residual biomass flow in place of a virgin source is an apparent sign of increased resource efficiency. This is the principle on which the circular economy is based. However, this increase in efficiency should be related to other sustainability and safety factors. Otherwise, it is possible that the use of a secondary resource flow will lead to more losses than gains for the material cycle. In this light, the preservation of or gain in natural, social and economic capital should not only be related to a gain in resource efficiency, but also set against other potential effects on health, environment and safety, such as impacts on climate, biodiversity, soil fertility and land use.

A shift in the use of residual biomass flows can, from the perspective of circularity, also have indirect consequences in other production chains/cycles. For example, the increased use of recycled cooking oil for the production of biodiesel has affected the use of oils in other sectors, e.g. the olechemical industry, which has increased its use of virgin palm oil as a result. In order to make well informed decisions about the application of residual biomass flows, the environmental, social and economic context should be considered. This can be done using methods that include different stakeholders in the decision process. These

methods use a tiered approach, starting with prioritization based on common knowledge and ending with complex considerations based on further research. For these different tiers, relevant sustainability indicators, including circularity, need to be found.



The three main components of an indicator system for including circularity in a sustainability assessment (Panel A) and the framework needed to assess residual biomass applications (Panel B).

Furthermore, specific goals and limits, which make up the boundary conditions, will help the transition to a more sustainable use of residual biomass flows. Further work is needed to develop methods for assessing the potential uses of residual biomass flows. This should have an international scope and not focus only on The Netherlands. It includes work on:

- An indicator system that gives a balanced view of the sustainability of a biomass flow. For this, indicators of environmental impact, of resource use and losses and of yield in terms of natural, economic and social capital are needed. See Figure A.
- The context to which the sustainability measurement must be related in order to find the optimal application of a residual biomass flow (Figure B). Defining this context involves the following:
  - Comparing the new and original residual biomass flows, taking into account the impact of the removal of residual biomass flow elsewhere.
  - Specifying the conditions limiting the residual biomass application (boundary conditions), e.g. safety standards, availability of raw materials and product requirements. These should be defined through consultation with stakeholders at policy, sector and product level.
  - The relevant indicators should be chosen on the basis of stakeholder input related to e.g. the geographic location and scale or specific residual biomass flow.

- Methods for identifying and assessing the risks related to new applications of residual biomass flows. Information on safety is often missing in development of new applications.

Samenvatting

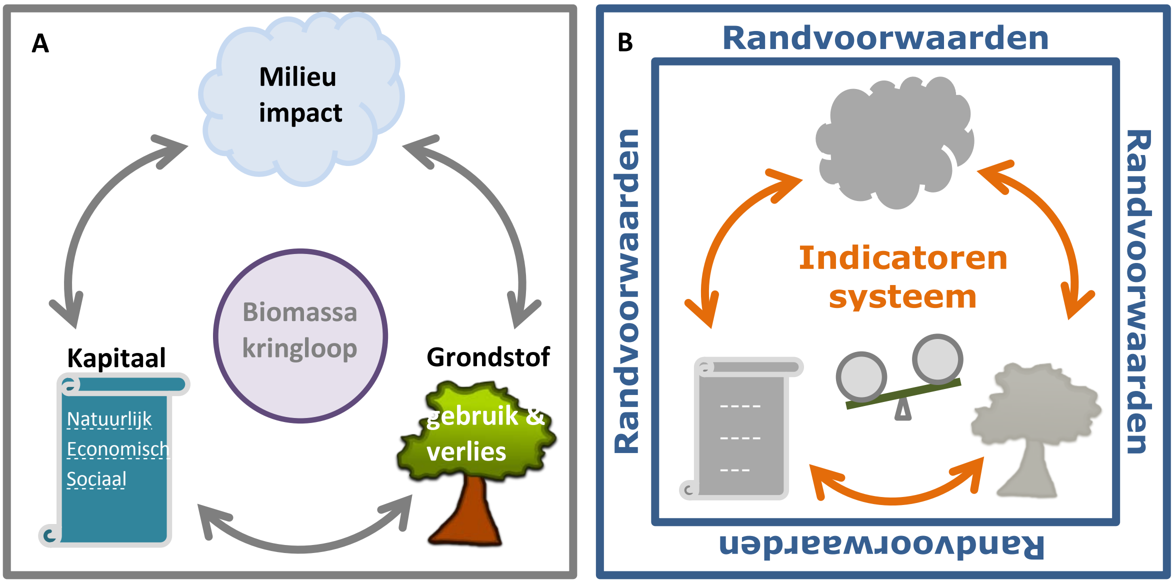
Benutting van biotische reststromen is een belangrijk onderdeel van de transitie naar een circulaire economie in Nederland. Veel van deze stromen worden al op een of andere manier nuttig gebruikt. Aan de ene kant is dit een voordeel, omdat het al gebruikelijk is om geen biomassa te verspillen. Aan de andere kant veroorzaakt dit een extra uitdaging om de optimale kringloop te vinden. Om de transitie naar een circulaire economie (CE) te optimaliseren en duurzaam en veilig te maken, is het nodig om na te denken over behoud van natuurlijk kapitaal en over nieuwe toepassingen van reststromen zonder dat dit leidt tot onaanvaardbare risico’s voor mens en milieu. Dit is het onderwerp van deze studie in opdracht van IenM waarbij ten eerste de kansen (potentiële waarde) en belemmeringen worden geïdentificeerd voor het hoogwaardig inzetten van biotische reststromen. Ten tweede wordt onderzocht hoe de principes van een CE in de huidige duurzaamheidsschattingen worden meegenomen. Ten derde worden deze bevindingen geanalyseerd en omgezet in aanbevelingen.

Biotische reststromen die schoon zijn hebben de grootste kans op een hoogwaardige toepassing. Een belangrijk aspect hierbij zijn de processtappen in de keten die dit beïnvloeden. Denk bijvoorbeeld aan de methode waarbij afvalwater wordt gezuiverd, maar ook het fosfaatmineraal struviet kan worden geproduceerd. Ondanks dat er nog onbeantwoorde vragen zijn over de potentiële aanwezigheid van pathogenen of contaminanten, biedt deze reststroom veel grotere kansen op verwaarding dan de oorspronkelijke reststromen: effluent of slib.

Het feit dat een biotische reststroom een primaire grondstof kan vervangen betekent dat de grondstof daarmee efficiënter wordt benut, deze komt zo immers terug in de kringloop. Dit is het principe waar de CE op gebaseerd is. Deze toegenomen efficiëntie moet echter wel op andere duurzaamheids- en veiligheidsaspecten getoetst worden, anders bestaat de kans dat een kringloop meer last dan baten heeft bij gebruik van een secundaire grondstofstroom (afwenteling). Hiervoor zou behoud of zelfs winst in natuurlijk, sociaal en economisch kapitaal niet alleen afgezet moeten worden tegen de toegenomen grondstofefficiëntie, maar ook tegen de andere potentiële effecten op gezondheid, milieu en veiligheid, zoals effecten op klimaat, biodiversiteit, bodemvruchtbaarheid en landgebruik. Een verschuiving in gebruik van een biotische reststroom uit circulair oogpunt kan ook indirecte gevolgen hebben in andere verwante productieketens/kringlopen. Zo heeft het verhoogd gebruik van herwonnen olie en vet voor biodiesel gevolgen voor de afzet hiervan in andere sectoren waar deze secundaire grondstof weer wordt vervangen door primaire palmolie.

Het is dus van belang om een geïnformeerde keuze te kunnen maken bij toepassing van biotische reststromen. Hiervoor moet het milieu-, sociaal en economisch kader in acht worden genomen. Om dit te doen kan gebruik worden gemaakt van de beschikbare methoden om stakeholders te betrekken in besluitvorming. Deze methoden zijn gebaseerd op een getrapte aanpak beginnend met prioritering op basis van vooral parate

kennis tot steeds complexere afwegingen op basis van verder onderzoek. De hiervoor benodigde duurzaamheidsindicatoren voor het kwantitatief vaststellen en wegen van de impact van keuzes in dit veld zijn nog niet allemaal even ver ontwikkeld.



De drie belangrijkste onderdelen van een indicatorsysteem om circulariteit mee te nemen in een duurzaamheidsanalyse (Paneel A) en het kader dat nodig is om toepassingen van biotische reststromen te toetsen (Paneel B).

Om de transitie naar een duurzame circulaire economie te maken is het nodig om doelen en grenzen te stellen die haalbaar en inpasbaar zijn. Hierbij is het van belang om niet alleen in Nederland, maar ook internationaal methodieken te ontwikkelen voor het afwegen van opties voor gebruik van grondstoffen uit biotische reststromen en biomassa in het algemeen. Dit vergt nadere aandacht voor:

- Een indicatorsysteem dat evenwichtig de duurzaamheid van een biomassakringloop weergeeft. Hierbij moeten indicatoren gebruikt worden die aangeven wat de effecten zijn op het milieu, de grondstofstromen en de toename in natuurlijk, economische en/of sociaal kapitaal. Zie Figuur A.
- Het kader waartegen de maat voor duurzaamheid kan worden afgezet voor het vinden van een optimale toepassing van biotische reststromen (Figuur B). Dit kader bestaat uit:
  - Een vergelijking tussen de nieuwe en oorspronkelijke toepassing van biotische reststromen. Hierbij rekening houdend met de impact van het wegvallen van een biotische reststroom elders.
  - Het vaststellen van de randvoorwaarden waarbinnen de optimale toepassing bereikt kan worden. Deze randvoorwaarden bestaan bijvoorbeeld uit veiligheidsnormen, de beschikbaarheid van grondstoffen en producteisen. Deze kunnen het beste worden vastgesteld met inspraak van verschillende stakeholders op het niveau van beleid, sector en product.

  - De keuze van de relevante indicatoren aan de hand van stakeholder-input gerelateerd aan bijvoorbeeld de locatie, schaalniveau of specifieke biotische reststroom.
- Methoden om nieuwe risico's behorende bij nieuwe toepassingen te kunnen identificeren en schatten. Dit is nodig omdat er vaak informatie hierover ontbreekt voor nieuwe toepassingen.

1 Introduction

1.1 Sustainable development

In September 2015 the UN published its Sustainable Development Goals (SDGs)[1]. These goals relate to 17 themes and have a broad scope, addressing the interconnected elements of sustainable development: People, Planet, Prosperity, Partnership and Peace (see Figure 1). Instead of addressing the dimensions of development separately, the SDGs aim to integrate the social, economic and environmental dimensions. With the focus now on the transition towards a circular economy, this set of elements of sustainability provides a framework which can serve as a prerequisite for a sustainable transition.

Figure 1. The five elements of the Sustainable Development Goals set out by the United Nations Environment Programme (UNEP): People, Planet, Prosperity, Partnership and Peace.[2]

Sustainable development

i There are natural limits to growth (quantitative growth).

ii The limits are dictated by the environment, and therefore all actions in any system must adhere to the carrying capacity of the local natural system.

iii Because environmental, economic and social systems are nested systems, all actions must be based on system thinking and account for multilevel influences.

Source: Farley and Smith[3]

Sustainable development is thus related to many areas of life on earth, including society, the environment and economics. There are several ways of assessing sustainable development in these different areas. For example, the UN has developed (and updated) a ‘capitals framework’ for measuring sustainable development, resulting in five capitals: financial capital, produced capital, natural capital, human capital and social capital.[5] There is considered to be ‘weak sustainability’ if trade between capitals is allowed, e.g. substituting environmental capital for human capital.[3] There is ‘strong sustainability’ if future generations will have the same amount of all the different types of capital, and there is no ‘trade’. The latter scenario can be achieved only when a shift is made from quantitative growth to sustainable development, this is strongly related to the environment. This concept of sustainable development is based on three rules as defined by Farley and Smith: (i) There are (known or unknown) natural limits to growth (quantitative growth); (ii) The limits are dictated by the environment, and therefore all actions in any system must adhere to the carrying capacity (or an estimated value for that) of the (local) natural system; (iii) Because environmental, economic and social systems are nested systems, all actions must be based on system thinking and account for multilevel influences.[6, 3]

In this report we focus on residual biomass and its potential role in an increasingly circular economy, with a specific focus on natural capital or the environmental- (‘planet’) element of sustainable development. It should be noted, however, that the other elements (Figure 1) should not be forgotten. This means, that in terms of capital: the financial, produced, human and societal capital cannot be forgotten. For example, the use of recycled materials as an alternative to a pristine resource might greatly reduce environmental impact but, if the social cost related to cleaning the recycled material is unacceptable, e.g. use of child labour or poor working conditions, it may not be considered a sustainable process.

We focus on residual biomass and the current use and potential development of circularity related sustainability indicators, including a short discussion on elements of sustainability, other than the environment/planet. This is because, until now, there have been several indicators and methods for identifying and quantifying environmental impact and resource efficiency, but not for identifying the degree of circular flow or material circularity. The Ellen MacArthur Foundation has recently introduced a mass-flow-based indicator specifically for the circular economy that can be applied to products or companies. However, this Material Circularity Indicator is aimed at technical cycles and materials from non-renewable sources. More work is needed to extend it to biological cycles and materials from renewable sources.[7]

The European Commission has published several reports on the need for increased resource efficiency and has suggested several indicators to measure this.[8] A good reason for this is that ‘what gets measured gets managed’.[9] Although resource efficiency is related to circularity and the principles it stands for, the reuse or recycling of resources is not necessarily included in the available indicators and indicator systems. In an indicator system, all relevant indicators should be measured to allow for optimization, not only those that are available. The EC has defined resource efficiency as measurable by three types of indicator, namely for socio-economic benefits, environmental impacts and resource use, see Figure 2.

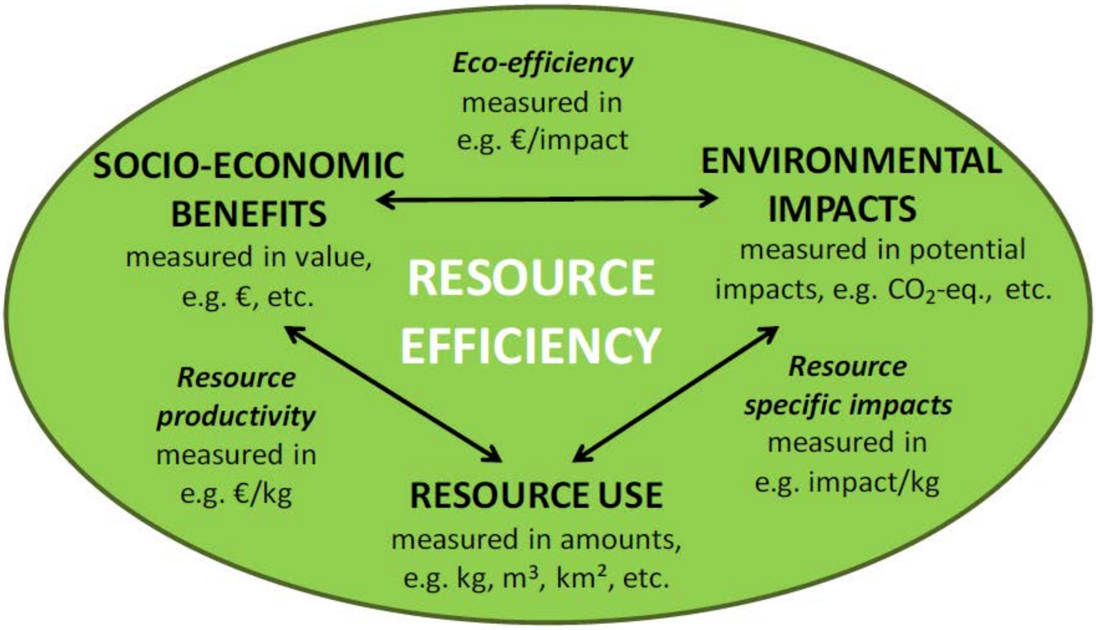
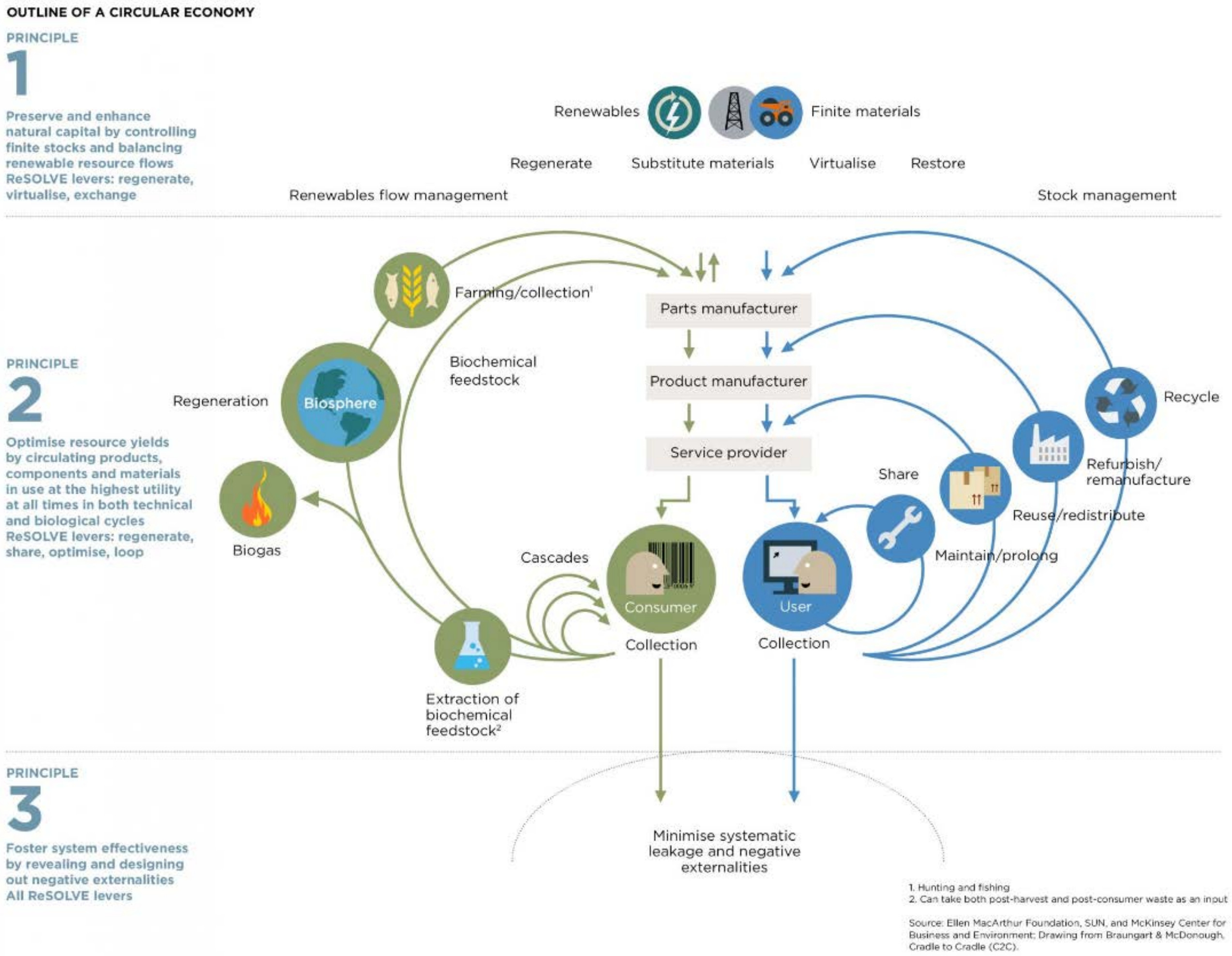


Figure 2. Resource efficiency as defined by the EU Commission's Thematic Strategy on the Sustainably Use of Natural Resources.[10]
Source: BIO Intelligence Service[9]

1.2 Circularity

Triggered by global concerns and the UN and EC roadmaps, the Dutch government, as well as private companies, non-governmental organizations and civilians, is trying to find ways to transition from a linear to a circular economy (Figure 3). In The Netherlands, residual biomass represents a substantial material flow (see Chapters 2 and 3 for details). Specific initiatives already exist including finding new uses for wastewater, beet waste and organic waste from households, with a focus on maximizing sustainability. The main problems at this moment are defining the relevant aspects and elements of sustainability to use for optimisation without depleting the systems capital (e.g. natural capital).

Natural capital
biodiversity, including ecosystems that provide essential goods and services, from fertile soil and multi-functional forests to productive land and seas, from good quality fresh water and clean air to pollination and climate regulation and protection against natural disasters.
Source: 7th EU Environment Action Programme



1. Hunting and fishing
2. Can take both post-harvest and post-consumer waste as an input

Source: Ellen MacArthur Foundation, SUN, and McKinsey Center for Business and Environment; Drawing from Braungart & McDonough, Cradle to Cradle (C2C).

Figure 3. The circular economy model indicating the three principles of the circular economy and its components for the technical (blue circles) and biological (green circles) cycle.
Source: Ellen MacArthur Foundation[12]

Around the turn of this century, the focus in environmental policy shifted from environmental issues such as conserving endangered species towards sustainable development. Economic activity and human well-being both have an impact on (natural) resource use and the environment. With this in mind, UNEP[11] has identified two key aspects of sustainable development: resource decoupling and impact decoupling. This is decoupling from economic growth and increase of overall human well-being, e.g. increase well-being without an increase in greenhouse gas emissions (see Figure 4). In order to achieve this decoupling a systemic change in the economy has to take place. The change from a linear to a circular economy will contribute to this resource and environmental impact decoupling by preserving and enhancing natural capital, optimizing resource efficiency and reducing negative impacts.

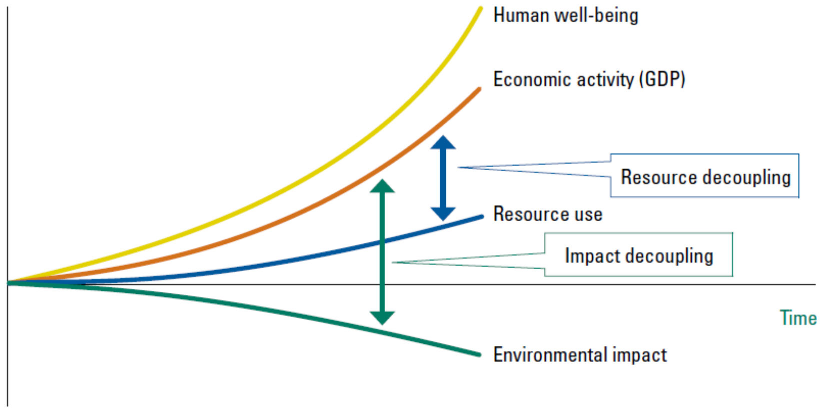


Figure 4. Illustration of decoupling human well-being, economic activity, resource use and environmental impact
Source: UNEP[11]

In the circular economy model by the Ellen MacArthur Foundation, a distinction is made between the natural and the technical material cycles (see Figure 3). They define three principles of the circular economy, which apply to both cycles.[12] The first principle is to preserve and enhance natural capital and control finite and renewable resources. The second principle, to optimize resource yields, is related to resource efficiency and this is where loops or cycles are formed. The third principle, to foster system effectiveness, is related to reducing losses and negative effects. The main difference between the technical and biological or natural material cycles is related to the second principle, where loops can be based on reuse within a product chain. For example, many agricultural products cannot be reused in the same way as a glass bottle (technical cycle) can be reused (glass-to-glass reuse). The by-products or waste derived from the use of an agricultural product is often transferred to another production process, e.g. the use of beet pulp in animal feed. This means that for residual biomass flows choices often have to be made regarding the transfer to other production processes. In order to increase efficiency these choices can be made according to the cascade principle (see Section 2.2). It is of course also possible to recycle nutrients in (nearly closed) natural cycles, e.g. by making compost from local organic waste for reuse as local soil fertilization.

Although several references are made to the work done by the Ellen MacArthur Foundation, the theory of the circular economy originated from various schools of thought: Cradle to Cradle, Performance Economy, Biomimicry, Industrial Ecology, Blue Economy and Regenerative Design. These schools of thought have more or less the same basic theory, but differ in their details and focus. Our basic assumption is that the circularity of a production process or biomass flow is increased when virgin material input and waste production is reduced in relation to yield.

The Dutch government, like those of many other countries, has a ‘green growth’ policy, with the aim of achieving sustainable development[13], and promotes the development of a circular economy. Recently the Dutch government initiated a government-wide circular economy programme aimed at integrating current activities and defining missing elements.[14] The current Waste to Resource programme (VANG), which focuses on creating loops of resources, both biotic and abiotic (Figure 5), is part of the effort to realize a transition from a linear to a circular economy.

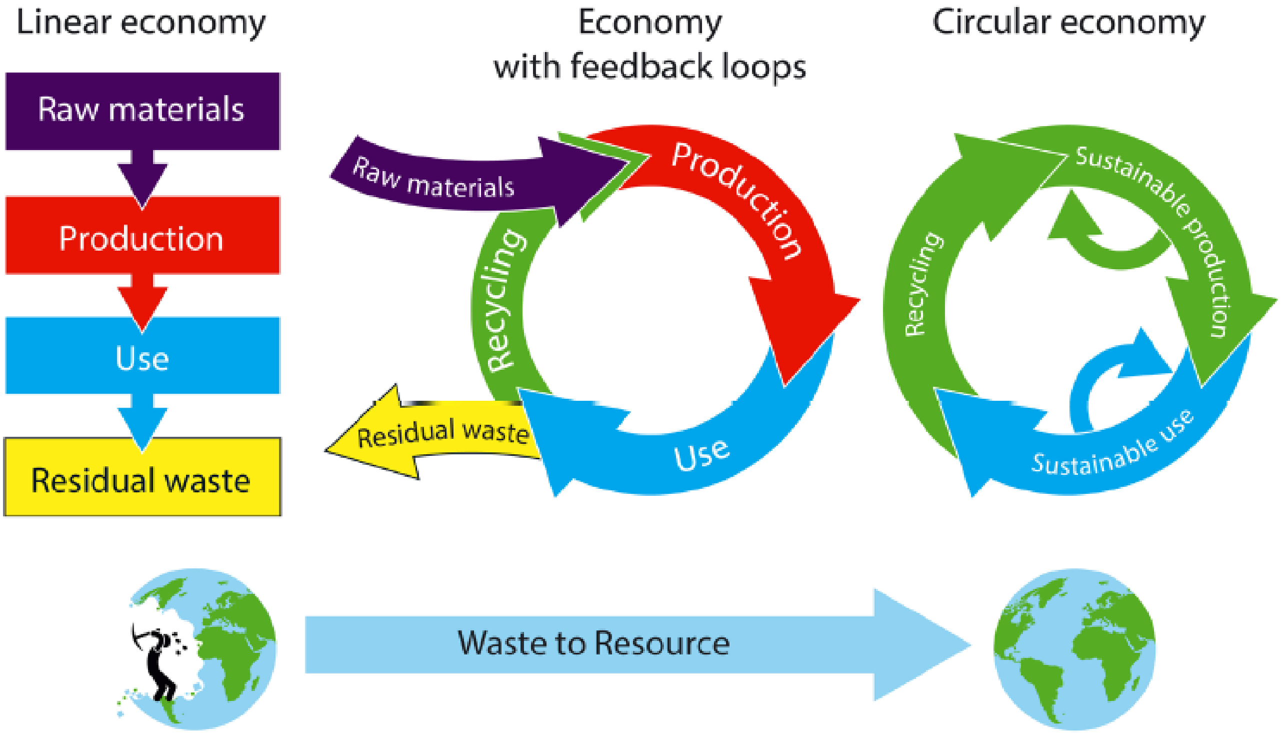


Figure 5. Dutch Waste to Resource programme (VANG)
Source: Annex 1 to the Letter to the House of Representatives headed Implementation of the Waste to Resource programme.[15]

To support this transition a sector-specific approach will help identify sector specific issues. Here we focus on the agricultural, food and biomass sector – specifically on organic waste, which comes from processes in agriculture, forestry, fishing, the food catering and retail industry, households and wastewater treatment plants. In The Netherlands, this residual biomass has an annual volume of almost 43 million tonnes (wet weight) and its use is worth €3.5 billion.[16] In the same report, Bastein et al.[16] estimate that there could be an increase in worth of €1 billion when the use of residual biomass is optimized using new techniques.

There is no denying that realizing this economic potential, whilst taking into account the basic principles of a safe circular economy (Figure 3), will lead to an increased sustainable development status. However, there are still several obstacles that hinder the transition to circularity. One such, is the absence of a method to include circularity in sustainability assessment of residual biomass. And from a policy perspective, another is the current regulations for waste relating to environmental safety. The use of waste flows must meet 'End-of-Waste' criteria to ensure safety as defined in the Waste Framework Directive (art. 6). However, producers (waste converters) of secondary materials must attest that their product fulfils these criteria taking into account the various waste flow reuse options. This is a costly and time-consuming exercise. For instance, there is no ready-made framework that can be used to declare a material to be End-of-Waste and ready for safe reuse. Furthermore, there is uncertainty on what environmental impacts need to be considered as part of an increased circularity in production processes and how to actually measure the increased circularity.

1.3 Aim and reading guide

The aims of the current study are, first, to make an inventory of the issues related to the optimization of residual biomass flows; second, to review the existing indicators and methods for assessing their environmental impact and sustainability, with a focus on increasing resource efficiency and circularity; and third, to analyze these findings and report conclusions and recommendations.

Nutrients are an inherent part of biomass, and although in the rest of the report this is for the most part not specified, the term residual biomass should be read as including the related nutrients and microelements.

In this report the issues specific to residual biomass, e.g. related to scale, cascading and regulation, are briefly discussed in Chapter 2. Chapter 3 gives a more detailed analysis of residual biomass flows in The Netherlands in terms of their availability, applications and risks. These issues are elaborated in Chapter 4 using two examples: the processing of beet and wastewater treatment. A selection of sustainability assessment methods are reviewed in Chapter 5, where the focus is on indicators of environmental impact and circularity, but in the last paragraph possibilities of including other elements of sustainable development are briefly mentioned. To highlight the importance of placing a sustainability assessment in context, applicable frameworks and methods for a tiered approach that includes stakeholder involvement are discussed in Chapter 6. In the concluding chapter, Chapter 7, the key aspects of this overview are summarized, and conclusions and recommendations are made. These should form the basis for progress towards a sustainable circular economy in the use of residual biomass.

2 Why residual biomass?

Residual biomass
A biomass flow can be considered residual when one or more of the following characteristics are met:

- It is not intentionally produced (e.g. the production chain is not modified for the production of this biomass flow).
- The biomass flow represents an economic value of less than 10% of the value of the main product.
- The biomass flow is released during a process other than a production process.

Source: NTA 8080:1 2015[18]

From an economic perspective, sectors related to residual biomass are important for a transition to a more circular economy. Here we highlight several aspects or issues for consideration in effort to increase circularity in (residual) biomass use. These issues, which are the result of a brainstorming session with experts in the field of residual biomass use and regulation, are briefly introduced and illustrated with some examples, such as nutrient cycles, which are an important aspect of residual biomass.

2.1 Scale

To begin with, there is an upper limit to the primary production of biomass, which is associated with the amount of sunlight reaching the earth; this has been defined in the context of the Planetary Boundaries Framework.[17] Biomass is used as a food, fibre and energy resource, resulting in residual biomass. Within the globally limited total resources, and in accordance with regional or local resource types and masses (e.g. residuals of maize), the effects of interventions by man on nutrient cycles vary in scale and by application. Non-local reuse, for example, may be technically feasible but costly because of the need for transport. Therefore, it is important to define the spatial and temporal scale of an environmental impact.

Spatial: International, regional, local

In nature, all nutrients are part of a cycle. For example, tree roots extract nutrients from the soil, which the tree uses to grow. In the autumn, the litter from trees is fragmented by soil fauna and then soil bacteria make the nutrients available for the next cycle. In the end, nothing is wasted in nature and, from a global perspective, all loops are closed. In the current global economy, agricultural goods are transported not only from one country to another, but also from one continent to another. The Netherlands exports a large part of its agricultural products: in 2015 the value of these exports was € 81 billion.[19, 20] About a quarter of these exports go to Germany. The Netherlands also imports agricultural products and resources. In 2012, The Netherlands was the third biggest agricultural importer from Brazil after China and the USA, whose imports were worth US$ 6.12 billion.[21] The impact of the import and export of agricultural products and resources on the nutrient cycles is likely different within The Netherlands (local or regional), Europe or other continents. In The Netherlands there is a surplus of nitrogen and phosphorus,[22] due to the import of cattle feed and artificial fertilizers. This results in an imbalance in the nutrient cycles and other associated problems, which should be evaluated as part of the optimization process. In theory, increasing circularity will reduce the imbalance.

Temporal
As mentioned above, there is a nitrogen and phosphorus surplus in The Netherlands. This was recognized in the late 1980s and measures to counteract its adverse effects have since been taken. In the 25 years since the first measures (up to 2011), the surplus of nitrogen and phosphorus decreased by 59% and 81%, respectively.[22] This example shows that in some cases it can take quite some time before measures have an effect. In other cases, the situation can change more rapidly. This means that an environmental impact also changes as the circumstances do. The use of a residual biomass flow for a specific purpose could be optimal in the short term, but technical improvements, changes in resource availability or geopolitical developments could make a different purpose optimal in the longer term.

2.2 Cascading

Cascading
Cascading components and materials means putting them to different uses after end-of-life across different value streams and extracting, over time, stored energy. Along the cascade, the material order declines (in other words, entropy increases).
Source: Ellen MacArthur Foundation[7]

In a circular economy, instead of residual biomass being considered as waste, it is used in other production chains and sectors. By extracting valuable biochemical feedstocks and cascading them into different, increasingly low-grade, applications when needed, the nutrients and energy are used as long and effectively as possible (Figure 6).[23] The aim is to optimize added value, which is one of the goals of a circular economy; it should be defined what is understood by value creation and how this is determined. When there is no further use for the residual biomass, its residue will return to the biological or natural cycle.

Both reuse in a cycle and return to the natural cycle should be optimized to avoid unexpected impacts. Often the materials for reuse contain toxic chemicals (e.g. plant protection products) or pathogens (dung), which can pose added risks to human health and the environment. For this reason, a safety assessment is needed. In terms of safety and resource efficiency, homogeneous streams are preferable to heterogeneous streams, as they facilitate the separation and purification of resources.

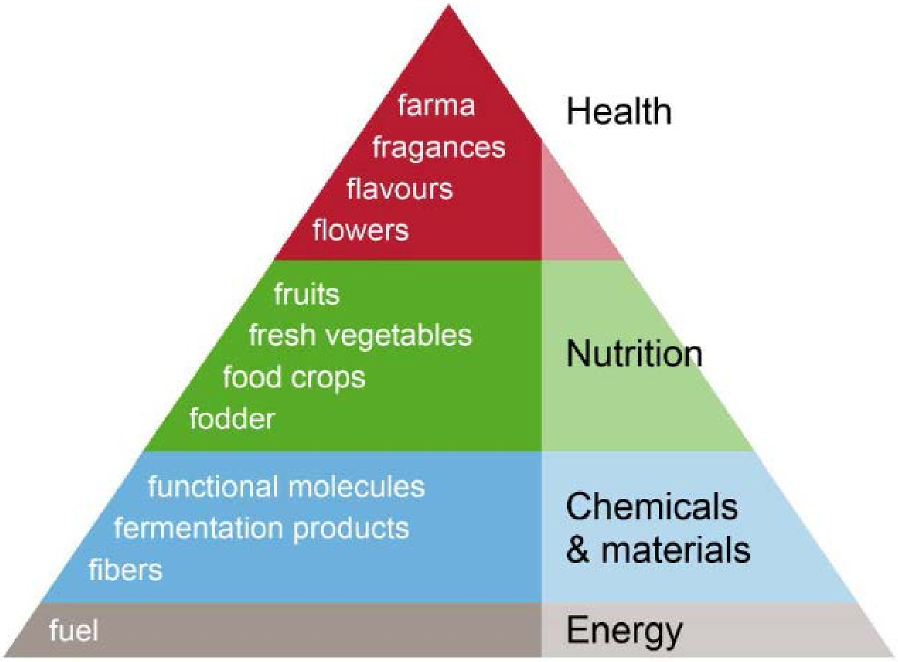


Figure 6. The cascade or worth pyramid for products related to biological cycles
Source: Smit and Janssens[24], adapted from Hoeven et al.[25]

2.3 Biomass vs. residual biomass

Residual biomass is related to the application of biomass, e.g. plants, certain types of micro-organism and algae are able to produce biomass via photo- or chemosynthesis. This biomass can be used for human food, animal feed or biofuel or as feedstock for the manufacturing of products (e.g. building materials or chemicals). During this process, part of the biomass becomes a residual (waste). At the different stages in the use of biomass it loses mass and energy and its composition changes. The end-of-life of an organism or product leads to residual biomass. This has an influence on the possibilities for reuse and recycling of residual biomass compared to cultivated (primary) biomass.

2.4 Dangerous substances

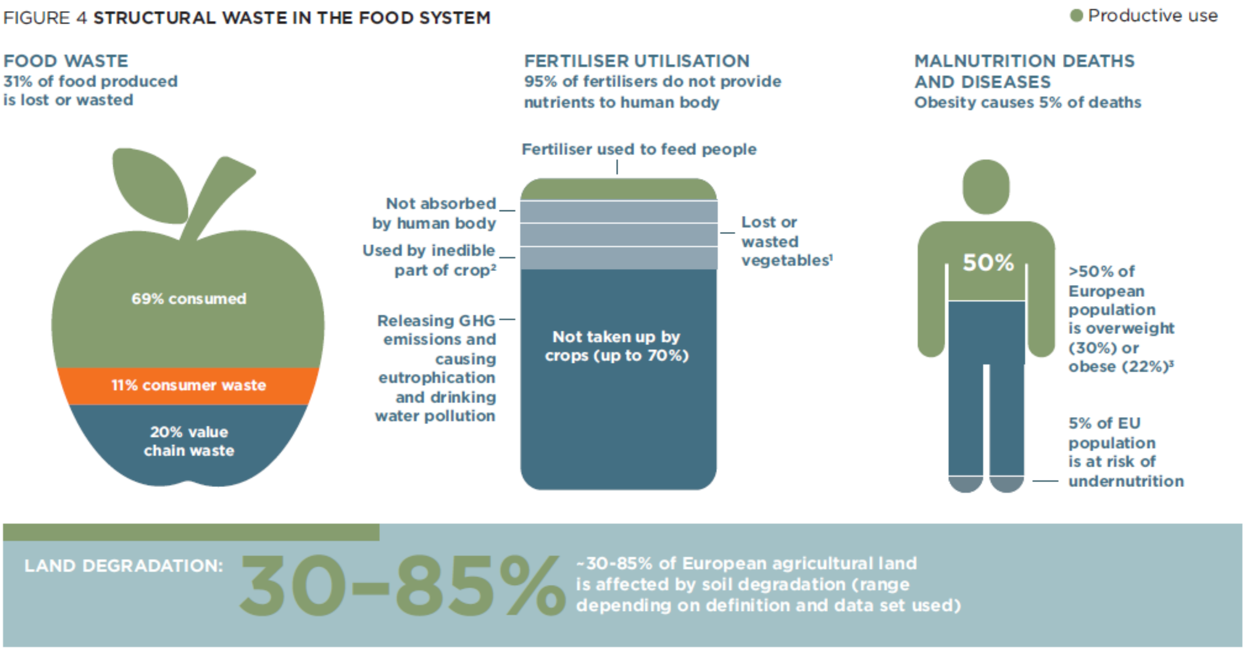
The recycling and reuse of residual biomass is limited when impurities or toxic substances are present. For example, cellulose from recycled paper can be used as an insulation material in construction, but to comply with fire and health regulations it has to be treated with flame retardants and fungicides. At the end of the useful life of the insulation material or the building, the cellulose is likely to contain a high concentration of flame retardants or fungicides, which might limit the possibilities for its reuse.

2.5 Efficiency and losses

An important aspect of circularity is the reduction of losses. Figure 7 reproduces an illustration by the Ellen MacArthur Foundation of waste in the food system. It shows that the process of food production and consumption is far from efficient. Residual biomass from the food system can be used as feed or as compost. However, optimization of the food system could prevent losses and make the system more efficient.

Resource efficiency is another aspect of circularity. In terms of value, the use as human food is a more efficient use of resources in comparison to animal feed or compost (see cascade pyramid in Figure 6). This view of efficiency also applies to maintaining soil fertility and avoiding land degradation, which is not always taken into account in the reuse of nutrients and organic carbon. The application of residual biomass flows, such as compost, play an important role in maintaining soil fertility and should be part of any optimization analysis conducted to move towards a more circular economy.

FIGURE 4 **STRUCTURAL WASTE IN THE FOOD SYSTEM**



1 In Europe ~46% of edible mass of fruit and vegetables is lost or wasted (FAO, Global food losses and food waste, 2011).
2 On average 23% of vegetable crops are not edible (peels, leaves, etc.). 3 BMI >25 (overweight) or >30 (obese).
Source: FAO, *Global food losses and food waste – Extent, Causes and Prevention*, 2011; MGI, *Overcoming obesity: An initial economic analysis*, 2014; WHO website obesity data; EEA, *Towards efficient use of water resources in Europe*, 2012; IFDC; Olle Ljungqvist and Frank de Man, *Under-nutrition – a major health problem in Europe*, 2009; Holly Gibbs and Meghan Salmon, *Mapping the world's degraded lands*, 2015.

Figure 7. Waste in the food system
Source: Ellen MacArthur Foundation[23]

End of Waste
Certain specified waste shall cease to be waste and obtain the status of a product (or a secondary raw material) when it has undergone a recovery (including recycling) operation and complies with specific criteria to be developed in line with certain legal conditions.
Source: Article 6 (1) and (2) of the Waste Framework Directive 2008/98/EC

2.6 Regulations

Wastewater contains phosphate minerals, which can be extracted as struvite. Struvite can be used as fertilizer in agriculture and partly replace artificial fertilizers, but current EU regulations leave market admittance of struvite up to the Member States. The waste label hinders the use of struvite, because of the lack of End of Waste criteria for this waste stream. This factor also limits the export of Dutch struvite to countries with phosphate deficits. In The Netherlands new legislation facilitates the use of struvite, but it has to be sanitized prior to reuse in order to kill pathogens. How this is to be done is not explicitly described and needs to be addressed. This case will be elaborated in Chapter 4.

2.7 Public perception

Residual biomass can be used in many types of product. Used cooking oil is collected and used as a fuel for diesel-engined cars. For several years now, households have been able to return their cooking oil at some 3,000 locations in The Netherlands. According to limited market polls[26] in 2012, 60% of the general public is willing to recycle their cooking oil. Another example is cellulose from wastewater, which can be reused in the production of toilet paper. In the latter case, the public opinion of this application could be influential for its success. Even though toilet paper containing recycled cellulose might comply with the required hygiene standards, public perception could be that it is not fit for use. Specific attention to public perception may be needed when the use of materials is objectively safe but blocked by negative perceptions, the opposite might also be applicable.

2.8 Trade-offs and unintended consequences

Used cooking oil

An average of 28,000 tonnes of cooking oil per year is used in Dutch households and 44,000 tonnes in professional kitchens. Most of the oil from professional kitchens is collected (95% in 2012), but only a small proportion of household oil (<17% in 2012).[26]

Used cooking oil is traditionally used as a raw material by the oleochemical industry for production of lubricants, paint and soap. However, because of the new application of used cooking oil for the production of biodiesel, the price of used cooking oil has risen above the price of fresh oil (2014). As a result, the oleochemical industry is using palm oil instead of used cooking oil, which likely leads to natural forest being cleared to grow palm trees in order to meet the demand for palm oil.

This illustrates the unintended consequences that can take place, which may on the one hand increase the economic yield of the residual biomass flow (e.g. due to a price increase) but on the other hand reduce natural capital (e.g. due to deforestation). The assessment of such trade-offs beforehand can contribute to making informed decisions on residual biomass applications.

Sources: KNAW[28] and D. Mijnheer[29]

The above-mentioned example of cooking oil used as biofuel shows that the diversion of residual waste streams to other sectors can have an impact on existing streams. The price of used cooking oil has increased because of its potential reuse as biofuel. Previously, used cooking oil was a resource for soap production. Therefore, the oleochemical industry now has to use palm oil as a resource for the production of lubricants, paint and soap.[28] The environmental impact of this shift in resources might outweigh the benefits of the reuse of cooking oil as biofuel, but a clear assessment of such comparisons is not easily made.

Eventually an integrated assessment of such trade-offs is needed in order to decide on the optimal application of a residual biomass flow. For this, information is required on the sustainability of each application. What are the consequences for the current processes or products and what are the future implications on different temporal and spatial scales? To answer these questions the involvement of stakeholders is needed, together with factual information on the supply chain of the product or process.

3 Residual biomass use: Economic value and limitations

3.1 Inventory of residual biomass

In this report, residual biomass is defined as a material flow containing biotic or organic material that is either not intentionally produced or represents only a low economic value compared with the main product or process (see text box on page 25). This definition of a residual biomass flow is part of the sustainability assessment framework set out in The Dutch technical agreement[18] (Nederlandse Technische Afspraak (NTA 8080-1:2015)), in which residual biomass flows are given some exemptions from the sustainability criteria that apply to virgin (non-residual) biomass.

In general, the economic value of residual biomass streams in terms of price per tonne is low. However, their total value is similar to or higher than that of pharma, compost and unprocessed/basic food products due to the high volume of residual flows.[31]

Table 1 presents a selection of residual biomass flows above 100,000 tonnes (dry weight) per year operating in The Netherlands, which gives an idea of their variety. Dry weight is often a good indication of resource availability, as water is often not the important compound in a residual biomass flow. This table is based on data reported by others combined with expert judgement and is not exhaustive.[16, 30] In some studies, mixed waste from households is considered to contain residual biomass, but it is excluded here due to the large amount of abiotic waste included in that stream.[16] Better separation could result in more organic household waste or other residual biomass flows. Only some of the residual biomass types could be categorized using NTA 8080 (see the NTA 8080 classification in Appendix B). Of the others, it is possible that some constitute an economic value greater than 10% of the main product, but this was not checked.

Table 1. Classification of residual biomass flows according to availability, risks and economics and application. Adapted from Bastein et al.[16] with added data[30, 35] and expert judgement.

	Availability		**Risks**		**Economics and application**		
Residual biomass flow[a]	**million tonnes dry weight per year in NL**	**Main source**	**Potential for risk pathogens**	**Potential for risk contaminants**	**Price (€) per tonne**	**Pyramid step current use**	**Current use**
Sludge from WWTPs	0.33	NL	high[c]	high	-50	low	biogas; heat
Organic waste from households	0.58	NL	medium	medium	-30	low/medium	compost; biogas
Public garden waste (e.g. branches)	0.45	NL	low	low	-25	low/medium	soil maintenance; compost; heat/energy
Roadside grass	0.24	NL	low	low	-25	medium	compost
Nature grass	0.35	NL	low	low	-25	medium/high	compost; paper
Poultry manure	0.81	NL[b]	high	medium	-15	medium	ash for artificial fertilizer
Cow manure	0.74	NL[b]	high	medium	-15	low/medium	biogas; fertilizer for N and P poor regions
Pig manure	0.88	NL[b]	high	medium	-15	low/medium	biogas; fertilizer for N and P poor regions
Champost	0.55	NL	low	low	-10		
Beet leaves	0.39	NL	low	low	0	medium	soil under ploughing
Potato foliage	0.44	NL	low	low	0		
Corn stalks and cobs	0.18	NL/EU	low	low	30	medium	cattle feed
Moist fibre/wet mash	0.11	NL	low	low	50	low/medium	cattle feed; biogas
Wet beet pulp	0.11	NL	low	low	50	low/medium	cattle feed; biogas
Straw	0.94	NL	low	low	150	low	soil maintenance (25%); stable floor cover; 2nd generation biodiesel
Grain by-products	0.22	NL/EU	low	low	210	medium/high	cattle feed; semolina
Dry beet pulp	0.28	NL	low	low	240	medium	cattle feed
Sunflower meal	0.49	NL/EU	medium	low	300	medium	cattle feed

	Availability		**Risks**		**Economics and application**		
Residual biomass flow[a]	**million tonnes dry weight per year in NL**	**Main source**	**Potential for risk pathogens**	**Potential for risk contaminants**	**Price (€) per tonne**	**Pyramid step current use**	**Current use**
Rapeseed meal	0.96	NL/EU	medium	low	300	medium	cattle feed
Used cooking oils and other oils	0.11	NL	low	medium	450	low/medium	cattle feed; 2nd generation biodiesel
Soybean meal	2.27	Global	medium	medium	505	medium	cattle feed
Slaughter/animal waste	0.65	NL	high	low	*-90 to 550*	low/medium	animal feed; biogas; heat; 2nd gen. biodiesel
Source:	*TNO 2013, Royal Haskoning DHV 2014*	*Expert judgement*	*Expert judgement*	*Expert judgement*	*TNO 2013, CE Delft 2013*	*Expert judgement*	*TNO 2013, Royal Haskoning DHV 2014*

PATHOGEN risk classification:
Low: Pathogens are limited in plant material and fats.
Medium: Pathogens may be an issue in protein-rich plant material.
High: Pathogen potential present due to waste from human or animal source.
NOTE: Mixed flows present extra issues. Specific applications may reduce pathogen content, e.g. making compost may reduce pathogen content due to heat, but there are often still risks due to cross-contamination between raw and processed material flows even if a sanitation step is included. In GFT mould is an issue.
CONTAMINANT risk classification:
Low: Contaminants can be present, but mostly known due to availability of data on the inputs in the main production process which also provides opportunities to redesign production processes to minimize contaminant transport.
Medium: Most contaminants present in these flows are known, but with significant uncertainty. The effort needed to get quality feedstock largely depends on the use case.
High: Contaminants are expected, but unknown. Significant effort needed for separation of quality feedstock.
PYRAMID STEP CURRENT USE classification:
Low: energy
Medium: as basic chemical building blocks and soil enhancement or fertilizers
High: as more complex chemical building blocks
a. Only flows of >100,000 tn/yr.
b. The manure is from animals in NL, but the feed is at least partly from international sources.
c. Human waste poses high risks.

3.2 Limitations due to pathogens and contaminants

One particular challenge that comes with new applications for a residual biomass flow is the new exposure pathways these might open for people and the environment to chemicals and/or pathogens. This may occur when a chemical contaminant or pathogen associated with a residual biomass flow is introduced to an industry that is not used to dealing with the potential safety hazards related to this new resource. Similarly, the unknown composition of a residual biomass flow (e.g. in the case of domestic wastewater) could be problematic. As listed in Table 1, all residual biomass flows that contain material from animal or human sources have a high potential for contamination by pathogens. Most plant-related biomass flows have only a low potential to contain pathogens; the exception is those that have a relatively high protein content, because this forms a good feeding ground for pathogens. However, mould and plant diseases can also be a hazard in plant-related residual biomass flows.

One has to consider that there may be additional transport of material, potentially containing pathogens, between industries. In the event of a pathogen outbreak a common method for preventing further spreading is a limitation on transport to and from a potential source. With the addition of other and new applications, a large increase in the transport movements to and from a potential source of pathogens can be expected. These industries are also likely to have differences in best practice standards for processing residual biomass. For example, the residual biomass from a professional kitchen may be used as cattle feed, but best practice related to the prevention of pathogen contamination in a professional kitchen is very different from that in a cattle feed factory, even if specific pathogen-reducing measures are taken such as sterilization.

Another example of how a new application can result in new exposure to pathogens is the use of biogas. In theory, biogas is burnt, and burning neutralizes pathogens, but some gas always escapes before ignition. The reuse of resources from domestic wastewater could also lead to new exposure routes of pathogens, if during the production process the biomass flow is not effectively sterilized. This issue is also relevant to the spread of antibiotic-resistant bacteria. In general, the exposure pathways that may develop due to the reuse of residual biomass need to be scrutinized in order to limit the potential for pathogen outbreaks.

Residual biomass streams can also contain chemical contaminants such as plant protection agents, which are mostly present in shells, peel or leaves. These are parts of plants that most often make up a residual biomass flow (see table 1). Additionally, natural plant products can accumulate contaminants from their surroundings, meaning that natural sources are not necessarily free from harmful contaminants. For example, heavy metal accumulation may occur in parts of trees that are often considered residual biomass, such as wood chips, leaves and prunings. This is due to uptake from their surroundings, through either the soil[32] or the air[33]. Such contaminants are present in the whole plant or tree, but for residual flows such as leaves, bark and roots some studies have shown higher metal concentrations compared to the woody parts. (Certain plants are specifically used for the purpose of soil remediation on account of their high metal uptake.[34]) Where these residual biomass flows are used in co-digestion with manure, heavy metals pose a potential problem, as they are liable to end up in the digestate, which is then spread onto soil, resulting in further contamination.

In the specific case of biogas production through co-digestion of residual biomass flows with manure, a working group of the Dutch Scientific Committee of the Manure Act (CDM) performs risk assessments for potential anorganic and organic contaminants. Based on the assessment a judgement is prepared for the Dutch Ministry of Economic Affairs, which decides whether to allow a specific residual biomass flow to be used in anaerobic digesters, in which case the digestate may be used as fertilizer. This is an example of a formalized judgement step in the process of ensuring the safe reuse of residual biomass.

The potential increase in risk of using a residual biomass flow rather than pristine biomass for a certain application must be considered, but there is currently no standard assessment method in place to evaluate potential risks.

3.3 Value: Material and application

Almost all residual biomass flows are already used for some purpose, except for mixed waste, which still largely ends up in landfills or incinerators. A selection of current applications can be found in Table 1. These applications have been assigned a value level in accordance with the classification of Lansink (related to the cascade pyramid – see Figure 6).[25] Applications for the production of energy are classified as ‘low’. Applications related to recycling – in the case of residual biomass, bringing nutrients or organic matter back into the agricultural cycle – are classified as ‘medium’. Reuses of compounds outside the agricultural cycle are classified as ‘high’. It should be noted that there are several possible values that can be attributed to an application or residual biomass flow, according to the effect this has on economic, natural or social capital. The value for all capitals should in theory be at least neutral in order for the flow to be sustainable. The value pyramid will change depending on the way these value types are applied, which could result in a different pyramid from the one illustrated in Figure 6.[31]

It can be seen that there is a large difference in the economic value of different flows, ranging from a negative value averaging €50 per tonne for sewage sludge to an asset worth about €500 per tonne for soybean meal or high-quality animal fat. This seems to be related to the content of the different flows. For example, sewage sludge and household organic waste are mixed flows with high processing and transport costs, and there is a medium to high potential for contaminants. All the flows that deliver a profit are of single origin and of relatively high purity, contributing to higher yields, for example in animal feed and biogas or biodiesel production. Most of these materials come from industrial sources; only used cooking oil partly originates from households.
There is only one example of an application at the ‘high’ level, which is the use of nature grass for paper production. It seems a limited amount

of grass is provided by the Staatsbosbeheer for this application.[30] The current economic value of this flow is given as calculated and reported in other studies.[16, 30, 35]
Overall, the table shows that a high potential for pathogens and contaminants and large variation in ingredients have an especially negative impact on use and consequently the economic value of these residual biomass flows, although there are several other aspects that play a role, such as the cost of processing and transport and the value of replaced virgin biomass or material use.

4 Case studies

4.1 Sugar beet residual waste

Introduction

Sugar beet forms the basis for sugar production in The Netherlands. Several residual flows are generated during the production of sugar, such as beet leaves, beet tails, beet pulp (wet and dry), molasses, Betacal, tare soil and process water. Beet leaves stay on the farmland as organic carbon input, but alternative uses are currently being investigated. Beet tails are used for biogas production. Beet pulp is used for animal feed or biogas production, but is also the subject of research into alternative applications.[36] Molasses is used for animal feed and alcohol production. Tare soil, Betacal and process water are not considered biomass and are not further discussed here. Further information on these residual flows can be found in the factsheet prepared by LEI Wageningen UR.[24]

The residual biomass flows originating from sugar production are not considered waste and they are all used in a cascade towards other applications to increase the total value of a sugar beet. There are many other agricultural production processes that put residual biomass flows to use; they rarely end up in a landfill. These flows are mostly used for animal feed, soil improvement or energy production. The discussion of this case is aimed at illustrating the environmental impact related to changes in the use of residual biomass flows and the scope used in such environmental impact assessments.

Environmental impact assessment

In a study by Croezen et al.[35] an interesting assessment of the environmental impact of biogas production was conducted, comparing different biomass flows, including that of beet pulp. They used a Life Cycle Assessment (LCA) method to compare the environmental impact of two primary residual biomass flows (manure and beet foliage), five secondary residual biomass flows (beet pulp, household organic waste, wastewater sludge, nature grass and roadside grass) and two cultivated biomass flows (corn and winter rye) in the production of biogas. They used six indicators of environmental impact: emission of greenhouse gasses (GHGs), acidification, eutrophication, production of summer smog, land use (direct and indirect), and toxicity due to heavy metals in waste and wastewater.

The use of beet pulp for animal feed was found to cause 1.5 times more GHG emission than the use of fossil gas.[35] This is due to the emission of GHGs by products that replace the beet pulp in animal feed. Not all beet pulp can fulfil the specs for animal feed, and for biogas made from this type of ‘off-spec’ beet pulp there is a reduction of CO_2 emission. Also for the other environmental impact indicators use of beet pulp that could be used for cattle feed increased acidification, eutrophication, summer smog, land use and toxicity.

Overall, the study concluded that any biomass flow used as a component of cattle feed is only partly sustainable. The study also used an economic indicator, namely the cost of using a certain residual biomass flow relative to that of using a fossil alternative for different applications of biogas. The combination of this value indicator with the amount of avoided greenhouse gas emissions falls in the category of circularity or resource efficiency indicators. Based on the economic cost of reduction of GHG emissions, secondary residual biomass flows such as nature and roadside grass, household waste and wastewater sludge actually make a 'profit' and reduce GHG emissions. The use of primary residual biomass flows such as manure and beet foliage does not make a profit, but the costs are still relatively low compared with the reduction in GHG emissions. The other residual biomass flow, off-spec beet pulp, and cultivated biomass, winter rye and corn have considerably higher costs compared with the reduction in GHG emissions.

A change in the application of a residual biomass flow causes a shift in material flow in other industries. This means that the use of a residual biomass flow such as beet pulp for biogas production instead of as a component of cattle feed can have a negative effect on the overall environmental impact. This is also true of cooking oil, where its use as a fuel has caused the oleochemical industry to use more palm oil instead.[28]

The assessment of such shifts is not easy, as it requires information from different industries. The study by Croezen et al.[35] took into account only shifts in material flows for corn and beet pulp. The development of methods that can help decision-makers to assess the indirect effects of new applications is needed. This should become part of any sustainability assessment framework, where a tiered approach should be taken, in which a full assessment is needed only in cases where there is likely to be a negative effect. Positive effects are also possible, and being able to quantify these will allow a stronger case to be made for a new application.

Comparing different material flows for the same application

Such assessments will also make it possible to compare resources. In the case of beet pulp, the use of off-spec beet pulp reduces the environmental impact, but other residual biomass flows, such as cover crops and manure, show even less impact.[35] In another study aimed at using virgin biomass primarily for energy production, the cultivation of sugar beet and Micanthus was compared with that of conventional crops.[37] Taking into account economic factors as well as environmental impact showed that in most cases bioenergy crops could not compete with conventional crops on suitable soils. Taking into account the spatial variation in environmental impact, however, proved valuable in this study, as Micanthus could compete with conventional crops in certain locations, partly as a result of its lower production costs.

The numerous research projects on new applications of residual biomass flows show a need for the development of guidelines and assessment tools that take into account the indirect effects of shifts in material flows. This will enable better and more informed decision-making on the use of residual biomass flows.

4.2 Wastewater as feedstock

Introduction

Wastewater contains several components, including biomass and nutrients, that can be used as resources. Domestic wastewater is generally collected in sewage systems and transported to wastewater treatment plants. It consists mostly of greywater (from sinks, baths, showers, dishwashers and washing machines), black water (the water used to flush toilets, combined with the human waste that it flushes away); soaps and detergents; and toilet paper (less so in regions where bidets are widely used instead of paper). Whether it also contains surface runoff depends on the design of the sewer system.

Traditionally, wastewater treatment involved the removal of pollutants to allow it to be discharged into the environment. This initially concentrated on carbon removal, but as environmental requirements became more stringent it was expanded to cover nitrogen and phosphorus removal. Generally, the treatment process results in a clean water stream that can be discharged into e.g. surface water, and a waste stream consisting of sludge. With increasing energy costs, more stringent environmental discharge limits and greater implementation of water-sensitive urban design, the economic viability of recovering water, energy and resources from wastewater is being considered more seriously.

There is abundant knowledge on the environmental (energy) and economic impact of the different treatment processes and available technologies.[38, 39] In particular, the dewatering of sludge demands a lot of energy (34 million kWh/year in Netherlands) as well of external resources like polymers. These polymers have a high environmental impact[38] and their use represents 10–15% of the total environmental impact of a wastewater treatment plant.[38] The drier the sludge, the more energy-efficient is the final treatment of the sludge. The dewatering phase is therefore a key phase to consider when trying to minimize environmental impact.

New technologies to extract nutrients and energy from wastewater are being developed.[40] The organic substances in wastewater can be converted into useful materials such as biodiesel, methane gas, electricity, polymers, bioplastics and an array of other products currently being investigated. In The Netherlands, recovery of energy has been established at a large scale and technologies for the recovery of cellulose and phosphate are particularly well advanced. The recovery of alginate and bioplastics is also being looked into. However, for several reasons (hygienic, legislative, technological)[41], market access for products based on these two resources is not yet available. The key issue here is the demand for End of Waste status for the recovered products or resources. With End of waste status, they are no longer subject to strict waste regulations, such as those relating to transport. One of the criteria for End of Waste status is that the use of the product or resource will not lead to an overall adverse environmental or human health impact. Assessment of this criterion is difficult in the case of products or resources deriving from domestic wastewater, because of the unknown risks associated with its human origin (e.g. pathogens, pharmaceutical residues). For further information on the wastewater treatment steps and the potential routes for the recovery of resources see the report by STOWA.[42]

Life Cycle Assessments (LCAs) are also used to evaluate the environmental impact of wastewater treatment plants.[43] Sustainability indicators are not commonly taken into account when comparing the standard operation of cleaning water to introduction of new techniques or processes focusing on recovery of resources. Current work in this area is reviewed.

Environmental impact assessment

In STOWA 2013–21,[44] the standard LCA approach is recommended for comparing the recovery of cellulose from wastewater by sieving with the traditional ('business as usual') use of a primary settling tank and regular sludge treatment. Depending on the final application of the recovered cellulose (fibre resource or carbon source) a different outcome is expected. The LCA approach is part of an ongoing study, but on the basis of first insights this report shows that sieving and the application of the separated material in products results in 25-80% energy savings compared with business as usual. In this sense (energy), the application as fibre resource is more promising, because application as carbon source uses less primary energy. However, carbon source as an application scores better on the eco-indicator 'land use', because no cultivation is necessary as opposed to regular (alternative) carbon resources (e.g. plant material). This shows that when making environmental impact assessments, the final application needs to be known. The choice of indicators (e.g. energy vs. land use) also determines the insights gained. This means that indicators need to be carefully selected and relevant.

Comparing different techniques for resource recovery

Some resources can be recovered at different stages in the wastewater treatment process. For example, phosphorus can be removed from separately collected urine at the beginning of the wastewater chain or from rejection water after digestion or after incineration from sludge ashes at the very end of the wastewater chain. Phosphorus (in the form of struvite) can be used in fertilizer products (e.g. for agriculture). Current (alternative) sources of the nutrients nitrogen and phosphorous for the production of artificial fertilizer are the atmosphere and the subsoil (mining). Phosphorus is not extremely critical for the EU in terms of recyclability. However, it is unclear how long global phosphorus reserves will last. And phosphorus is critical in terms of geographical concentration, geopolitics and substitutability.[45] There is a global phosphorous shortage.

Dansschutter et al.[46] used an LCA in which the recovery of phosphate is accounted for to compare different phosphate removal routes at the WWTP Amsterdam West. In this case, the recovery of struvite from digested sludge is the most environmentally friendly option, because amongst others the dewatering of the sludge is improved (from 22% to 25% dry matter, and 10–20% lower polymer use), which improves the calorific value of the remaining sludge, resulting in higher electricity production. The possibility of recovering phosphate is an important factor in the score of the LCA assessment, as phosphate from mining will become scarce between 2030 and 2050.

Afman and Korving[47] compared different sludge incineration processes for SNB (N.V. Slibverwerking Noord-Brabant), including scenarios with phosphate recovery, using an LCA. Their results show that the incineration process has a lower environmental impact if phosphate is recovered from the ashes than if there is no phosphate recovery. As in the previous study, the lower impact was found to be mainly caused by the replacement of fossil phosphate ore. The use of high-pressure kettles also lowers the environmental impact, in this case because of the generation of energy, which partly compensates for the energy use of the original process.

Remy and Jossa[48] analyzed 10 selected processes for phosphorus recovery from sludge, sludge liquor and ash to assess their potential environmental impact, following the LCA method. Different processes can be used to extract phosphorus from sewage sludge, sludge liquor or ash from mono-incineration. These have been developed, tested or already realized in full-scale in recent years. However, these pathways and processes differ in the amount of phosphorus that can be recovered in relation to the total phosphorus content in sludge as well as in the quality of the recovered phosphorus product. There are also differences in the required energy, chemicals, fuel and infrastructure for phosphorus recovery. The assessment shows that pathways and processes for phosphorus recovery differ heavily not only in the amount of recovered phosphorus, but also in energy use and related environmental impacts (e.g. GHG emissions). Direct precipitation in sludge/liquor (struvite) has side benefits (dewatering, return load, low energy/GHG footprint) but limited phosphorus yield (<12%) and is applicable only in bio-phosphorus plants. Sludge leaching has higher phosphorus yield (50%) but high demand of chemicals and high energy use/GHG footprint. Ash processes can recover up to 97% with reasonable energy use/GHG footprint but are dependent on mono-incineration (= low energy recovery, high GHG footprint).

Comparing multiple resources from the same material flow
It is not always possible to combine the recovery of multiple resources from a specific wastewater stream. This is due partly to technical limitations. When deciding which resource to focus on, relevant legislation, the existing infrastructure, the state of technological development and the market for products (economic valorization) all need to be taken into consideration. Some assessments are based on energy balance. However, a more holistic environmental impact assessment is not conducted. Comparing overall environmental impact between recovered resources is not common practice, possibly because the state of the art is not yet at the concrete product level, but mostly at the level of the technology used to recover resources. A limited comparison between alternative resources is possible here, but a more holistic comparison will only be possible when the final application or product is known.

However, Fooij[49] explored strategies for resource recovery from Amsterdam’s wastewater that might enable coherent and adaptable resource recovery policy-making. The four strategies that were developed each focus on the maximum recovery of one product: alginic acid, bioplastics, cellulose and phosphorus. However, the strategies also include the recovery of the other resources when this does not limit the recovery of the focus product. Financial considerations, such as the cost of a strategy, revenue from the sale of recovered products and the market conditions for these products, are excluded. The study concludes that bioplastic and alginic acid production are competing, but that the decision between these two strategies can be postponed. Cellulose recovery is also competing with these two strategies (when a fine-mesh sieve is installed, more cellulose and less sludge and biogas are produced) but is a no-regret measure in the short term because bioplastic and alginic acid production are still under development and will most likely not be implemented before cellulose recovery reaches its return on investment. Furthermore, the three phosphorus recovery methods considered all have advantages and do not have significant disadvantages, so implementation of these is possible. Finally, thermal hydrolysis is a win–win situation, since it increases biogas production and is probably also beneficial for alginic acid and struvite production.

Comparing different material flows for the same application
The domestic wastewater route can be compared with traditional resource recovery routes. For example, cellulose from wastewater or from waste paper; phosphorus from wastewater or from mining. One of the most important characteristics of domestic wastewater is that it mainly consists of human waste streams, with significant risks of contamination by micro pollution and pathogens. This results in higher efforts (energy, money, resources) to eliminate these risks, or a smaller range of final applications for which the recovered resource can be used (for example, excluding applications with human exposure). Such comparisons have been made but are generally based on business, energy or other practical factors. Other sustainability indicators have not been used for this comparison.

For example, struvite from wastewater from the potato industry is already legally admitted to the market. This wastewater stream is highly controlled and the pollution is generally known and technically removable. For struvite from domestic wastewater, however, it has been a much greater struggle to ensure safety and lift legal limitations. Since 2015, struvite from domestic wastewater can be sold on the market provided that it is sufficiently hygienized. However, it is not yet clear what treatment process is to be used to achieve this. Furthermore, in The Netherlands there is a manure surplus, and livestock farmers that wish to use the derogation under the Nitrate directive are forbidden to use artificial fertilizer. This competition with manure limits the national market for fertilizer from recovered phosphorus in the livestock industry. For agriculture and horticulture there might be a Dutch market for struvite if quality requirements are met (Good Agricultural Practices).[50]

Another example of a comparison between material flows is between cellulose from recycled paper and from wastewater.[44] Taking only economic aspects (processing costs) into account, the two sources of cellulose were found to be competitive. However, indicators for environmental impact were not taken into account.

The complexity of a residual biomass stream such as wastewater requires a complex methodology for the assessment of environmental impact and the overall sustainability of new techniques. Developments in wastewater treatment show the way forward in the transition to a circular economy by moving towards providing resources and reducing loss due to sludge incineration and still ensuring the protection of our aquatic and other natural capital.

5 Assessment methods

5.1 Review of current sustainability indicators

Here we review existing methods and indicators for assessing the environmental aspects of sustainability. There are several publications, guidelines and criteria available on sustainability indicators related to the environment. [5, 8, 9, 18, 51–58] From a purely environmental perspective, two types of indicator are important: (i) those that quantify the impact on the environment and (ii) those that quantify resource use and waste generation. However, the assessment of resource efficiency and circularity, in which we are most interested, also requires an estimate of the yield or utility of the product or service. This means a quantification of the benefits provided by the product or service. In theory a combination of these types of indicator will result in an indicator of resource efficiency or circularity (see Figure 2). This combination of types of indicators (Environmental impact, Resource use and loss and Yield) is a measure for resource efficiency and circularity. In the following, we will provide details of the different methods currently available to quantify the sustainability and, in particular, circularity of a production chain or resource flow, and highlight their commonalities and differences. For an overview see Table 2.

Note that the utilization of any such metric, such as for environmental impact, is not absolute and should be seen as relative to an option for change (e.g. compares two scenarios). That is, the judgement as to the degree of optimization that can be realized is based on a comparison between the business-as-usual option (e.g. linear economy scenario) and an alternative that contributes to the circular economy, taking into account laws and regulations. This may yield simple results, when all metrics suggest lower impacts and higher benefits. Results are more complex when a series of metrics of impacts show different degrees of impact change – as this requires the weighting and aggregation of 'the net best option'. When one or a few metrics signal potential harm, whilst others are (clearly) positive, it becomes a complex assessment. An example of this scenario is the use of residual biomass for biogas production, which results in a large reduction in impact due to GHG emissions but an increase in impact due to chemical contamination related to certain residual biomass streams entering the production facility and the digestate leaving it for fertilizer use. For this reason, only specific residual biomass flows are allowed based on a risk evaluation.

Environmental impact

The environmental impact of a process is defined by the change in quality of the natural environment and the services it provides.

There are several methods available that provide a measure for impacts on the different environmental compartments.[18, 53] The best-documented and most studied environmental impact is the emission of GHGs, which affect the earth's climate.[8, 18, 51-53, 59, 60] Other indicators of impacts on the different environmental compartments include ozone depletion and creation,[52, 60] aquatic and terrestrial ecotoxicity,[52, 60] soil acidification potential,[52, 60] soil carbon stock,[18, 51, 60] aquatic and terrestrial eutrophication potential.[52, 60] These are indicators that have an already defined method of quantification (though the search for good indicators is always an ongoing effort). Other aspects that are taken into account but have less clearly defined quantitative indicators are biodiversity and land use change.

The impact on biodiversity is commonly related to the impact on protected or vulnerable natural areas or systems. The EU Resource Efficiency Scoreboard shows three indicators of biodiversity: the index of common farmland bird species, the area under organic farming and landscape fragmentation. Biodiversity is affected by several other environmental impacts, such as eutrophication, soil carbon stock and ecotoxicity. However, it is often not clear to what degree these impacts will affect biodiversity negatively. In addition, spatial variation in these impacts can be large, so assessing location-specific impacts is needed, e.g. identifying vulnerable areas. This is particularly relevant to the assessment of biodiversity. A possible method of doing this is to map these impacts and the natural capital spatially.

In most methods the environmental impact of land use change is defined by identifying the current functions or use of land that should not be changed in order to be sustainable. This is the case for the NTA 8080-1:2015 sustainability criteria for biomass, which state that the production of biomass from land with high carbon stock is not considered sustainable. On land, soil delivers certain services, the natural capital, but the way it is used, land use, is an important factor for several environmental impacts, such as the emission of GHGs or change in soil carbon stock.

Most of the methods to assess environmental impact have a different goal and scope (see Table 2) in relation to residual biomass:

- The Dutch technical agreement 8080[18] (NTA 8080-1:2015) is a set of Dutch sustainability criteria for biomass. It defines sustainability criteria for produced and residual biomass used for bioenergy or bio-based products. Although NTA 8080 has defined sustainability criteria for all the categories of environmental impact, only GHG emissions is used as a quantitative indicator.
- The Agricultural Cycle Test[51] (kringlooptoets) is aimed at agricultural production and consumption and is still under development. It currently uses only qualitative evaluations of environmental impacts in relation to measures taken to improve production or the sustainability of the agricultural production cycle.
- ReCiPe[61] is an often used method for effect assessments in LCA. It includes quantitative indicators to assess the environmental impact of all types of products and materials, including residual biomass.
- The Product Environmental Footprint[60, 62] (PEF) is aimed at indicating the environmental impact of any consumer product and is still under development. PEF include quantitative indicators to assess the environmental impact of all types of products.
- The EU Resource Efficiency Scoreboard 2014[8, 9] was created to stimulate the decoupling of economic activity from resource use

and environmental impact. It includes quantitative indicators, but on a national scale, meaning that the indicators are less useful for assessing specific products or biomass flows.
- The Circularity Indicator developed by the Ellen MacArthur Foundation[7] is aimed at technical cycles and includes only limited suggestions for taking environmental impact into account. It requires adaptation for use with residual biomass.
- The method according to the Dutch Building Decree[52, 58] includes a method for assessing the environmental impact of building products, so has only limited applicability to residual biomass.

Table 2. Current strategies for measuring the sustainability of different production processes focused on environmental impacts, resource depletion and waste and resource efficiency or circularity. More details on these indicators can be found in Appendix A.

	NTA 8080-1:2015	**Agricultural Cycle Test**	**ReCipe**	**Product Environmental Footprint**	**EU Resource Efficiency Scoreboard**	**Circularity Indicators (EMF)**	**Dutch Building Decree**
Environmental impact							
Climate / air	**x**	**x**	**x**	**x**	**x**	**x**[a]	**x**
Water	**x**	**x**	**x**	**x**	**x**	**x**[a]	**x**
Soil	**x**	**x**	**x**	**x**	**x**		**x**
Biodiversity	**x**	**x**			**x**		
Land Use	**x**	**x**	**x**				
Resource use and waste							
Raw material		**x**	**x**	**x**	**x**	**x**[b]	**x**
Renewable material					**x**		**x**
Reuse and recyclability					**x**	**x**[b]	**x**
Waste flow		**x**	**x**[b]		**x**	**x**[b]	**x**
Hazardous or toxic waste			**x**[b]				**x**
Resource efficiency and circularity							
Resource efficiency / Circularity		**x**			**x**	**x**	

a. Part of suggested complementary indicators.

b. Data on this topic is needed for the calculation, but it is not defined as an independent indicator.

Resource use and waste

Sustainability goes further than reducing impact on the quality of the environment: resource use and waste are also important aspects, especially in the interest of creating circular production chains. The basis for sustainable resource management can be given by the principle of the three (or more) R's: reduce, reuse and recycle.[6] Implementing the principles of the three R's in the resource management of a production process contributes to the transition to a circular economy, although in the case of residual biomass, the first and last of these are the most important in food- and energy-related cycles, where reuse is less relevant. The reduction of waste going to landfill and more and better use of residual flows is important for the transition to a circular economy.

Some waste is inevitable, as no process is without some loss of energy or material (e.g. the degradation of materials in a production cycle), given the second law of thermodynamics. However, pollution is important to consider in early stages of a production cycle, because contamination by hazardous or toxic compounds reduces the potential to use or recycle residual biomass flows (see also Section 3.2). Residual flows that are deemed too hazardous may be sent to landfills, which should be avoided. This highlights the importance of product and production chain design in maximizing the safety of residual flows.

Sustainable resource use

- Renewable resources are not used at a higher rate than the rate of renewal.
- Non-renewable resources should not be used at a higher rate than alternatives could be developed in time before those resources are exhausted.
- The rate of pollution emission should be adjusted to the rate at which the ecosystem can decompose and adsorb the discharged pollutants.

Source: Flourishing within Limits to Growth[11]

Resource use is taken into account by all the reviewed methods (see Table 2), except for NTA 8080. This is done by quantifying the use of raw materials and specific compounds such as water, nutrients and fossil fuel. However, only the EU Resource Efficiency Scoreboard and the EMF Circularity Indicator explicitly take account of whether materials are renewable, reused or recycled. Because the reduction in use of virgin resources is an important aspect of the transition to a circular economy, an explicit distinction in all methods is needed between the use of virgin, bio-based/renewable and residual materials.

Because of the importance of residual flows in a circular economy, these flows need to be taken into account in sustainability assessment methods. A way to do this, is the allocation of impact to other products that use a residual flow from the main product, this is not standard practice yet. For example, in the results of a recent evaluation of the environmental impact of food consumption in The Netherlands, the impact could be reduced due to the use of residual biomass flows, but this was not part of LCA method used.[63]

Waste flows and levels of hazardous or toxic waste are considered to some extent in most assessment methods, but not as an endpoint; rather as an intermediate point used to calculate or estimate environmental impact in terms of toxicity (human and terrestrial or aquatic ecotoxicity) and eutrophication. If these flows can be made explicit (e.g using a new aggregated endpoint) the potential availability of materials for a new application can be made visible. Specifically for residual biomass there are some important waste- and resource-related issues that need to be taken into account in an assessment: (i) residual biomass is feedstock from recycled biomass waste, (ii) the purity of or safe levels of hazardous substances in residual biomass feedstock, (iii) the minimization of losses of biomass, e.g. by increasing recycling efficiency, and (iv) competition of residual biomass with virgin biomass feedstock.

Circularity and resource efficiency

Most of the current waste and resource management strategies can be characterized as representing an intermediate stage between a linear and a circular economy, the so-called chain economy with recycling.[64] There are additional aspects that need to be taken into account when considering the goal of a fully circular economy. The above-mentioned categories of indicator – environmental impact, and resource use and waste – provide a good measure of the natural resources that contribute to a production chain and the impact their use has on the environment. This is the basis for the creation of a more circular production chain, but it is not enough. The degree of circularity of a production chain should also be quantified in terms of an assessment of its benefit or yield. This could simply be the yield of a production process in terms of volume or mass, or its economic value. More complex assessments of social and natural capital gained can be made as well.

Indicators that are directly aimed at supporting the principles of the circular economy are being developed. [7, 9, 51] These also measure profit- and people-related elements of sustainability (Figure 1) and include an indicator of socio-economic benefits, in addition to the previously mentioned indicators for environmental impact, resource use and waste (planet-related aspects).[9] However, including the social element of sustainability using quantitative indicators is not trivial. In general, few methods are available for measuring or indicating both the social benefits and the economic benefits of a production chain. As part of the UN's sustainability goals[1] a set of 100 indicators is under development, which includes indicators related to social aspects.[65] For more information see Section 5.3.

The Ellen MacArthur Material Circularity Indicator quantifies benefit as the yield of a production process and the product lifetime, which are compared with the current industry average product yield and lifetime.[7] The Agricultural Cycle Test considers the change in yield of agricultural products when new processes are implemented or feedstock flows changed in order to improve circularity.[51] In the EC's report[8] on resource efficiency indicators, it was suggested that Gross Domestic Product (GDP) be used as indicator of benefit. This has resulted in the use of resource productivity, based on the materials (resources) used to produce the products and services (GDP) available in the market, as the lead indicator of resource efficiency at a national level.[8] Potential alternatives to GDP that also consider well-being are the Happy Planet Index[66] or data from the European Quality of Life Survey.[67]

In principle, the Agricultural Cycle Test is the method most fit for the purpose of assessing the circularity of residual biomass flows, but it is currently only qualitative and mainly based on expert judgement. The method assesses the nutrient efficiency (resource use) by taking a measure of the loss of nitrogen, phosphate and organic carbon. In addition to water, they are some of the most important resources for agricultural production. The product of the agricultural yield and nutrient efficiency indicates the circularity of the material cycle. By also taking environmental impact into account, the sustainability of this circularity could also be assessed.

In the EU Resource Efficiency Scoreboard, resource productivity is used as an indicator of circularity. This is applied to the national scale by calculating the materials used to produce the products and services available in the market indicated by the GDP, resulting in a resource productivity factor in euros per kg of material used.[8] In these terms, in 2013 The Netherlands had the highest resource efficiency in the EU-27.

Although such combinations of indicators are starting to be used to assess circularity and resource efficiency, most of the commonly used methods to assess sustainability do not include them.

5.2 Sustainability assessment of residual biomass

Current methods

Because NTA 8080 has defined sustainability criteria for residual biomass use, it can be applied relatively easily. This method does a good job of setting out criteria and asking questions about a large range of environmental impacts related to the use of residual biomass. It does not, however, include measures of resource use or waste making it unfit when circularity is deemed important.

For residual biomass the Agricultural Cycle Test is a promising method under development that includes accounting for waste and resource use, focussed on nitrogen, phosphorus and organic matter, coupled to the yield of agricultural products as a measure of economic value. Because agriculture and the material cycles relevant to it are closely related to residual biomass flows, this method seems better equipped in assessing circularity than the Ellen MacArthur Material Circularity Index at this point.

The Agricultural Cycle Test and the NTA 8080 complement each other in a sense, focusing on circularity and environmental impact, respectively. Although the Agricultural Cycle Test is also intended to include environmental impact (see Table 2), it is currently not clear how this should be done. Additionally the scope of resources taken into account is rather limited (nitrogen, phosphorus and organic matter). The method would gain in scope, if water and other components such as fibres for paper or clothing, polymers for bioplastics and proteins for cattle feed were added. NTA 8080, although limited to criteria for environmental impact, has much broader applicability and can be used for a greater number of production chains.

Assessing the environmental impact of residual biomass flows is not limited to the use of the indicators and criteria included in NTA 8080. There are several other methods available for calculating environmental impact in terms of GHG emission equivalents, e.g. ReCiPe or PEF. ReCiPe contains the effect indicators used in a LCA that also accounts for raw materials needed, impacts on water and soil quality and land use. Although indicators for circularity are not part of ReCiPe, an LCA approach in general is possible for investigating the circularity of production processes using residual biomass flows, but requires expert knowledge and more effort because there are no standardised rules yet to take circularity into account. This means that only case-specific studies can be conducted.[24, 35, 48, 79] For example, see the cases on use of residual flows in sugar production from beet and wastewater treatment in Chapter 4.

Mapping residual biomass

The spatial aspects, such as heterogeneity of available residual biomass flows and the spatial scale can be important aspects to consider in a sustainability assessment. The Agricultural Cycle Test focuses on different scales, such as local (e.g. a farm), regional (e.g. The Netherlands) and global, in order to assess the implications of different actions for improving circularity. Regarding spatial information on availability there is already considerable information available in The Netherlands in terms of statistics and maps (Figure 8). There are also several map based marketplaces where users and producers of residual biomass can ask for or offer products, e.g. www.biocontact.eu, www.biomassa.eu, www.biomassadhz.nl and www.oogstkaart.nl. The next step would be to incorporate part of the sustainability assessment in these maps to identify locations where certain applications or biomass flows are preferable over others.

A framework developed by van der Hilst et al.[37] included a spatial component in order to find locations where little negative environmental impact or even a gain in natural capital could be identified for the production of bio-energy crops. In their case study of the cultivation of sugar beet or Micanthus as a crop for energy production, they came to the conclusion that there is no location where there would be no negative impacts. They found that the highest correlation was between environmental impacts and current land use or soil type was due to the effect of indirect land use change.

This shows the possibilities in adding a spatial component in a sustainability assessment. This might become more important when considering the transition to a circular economy. Spatially explicit screening tools should be developed for stakeholders to make well-informed decisions, in order to help find optimal residual biomass sources and applications.

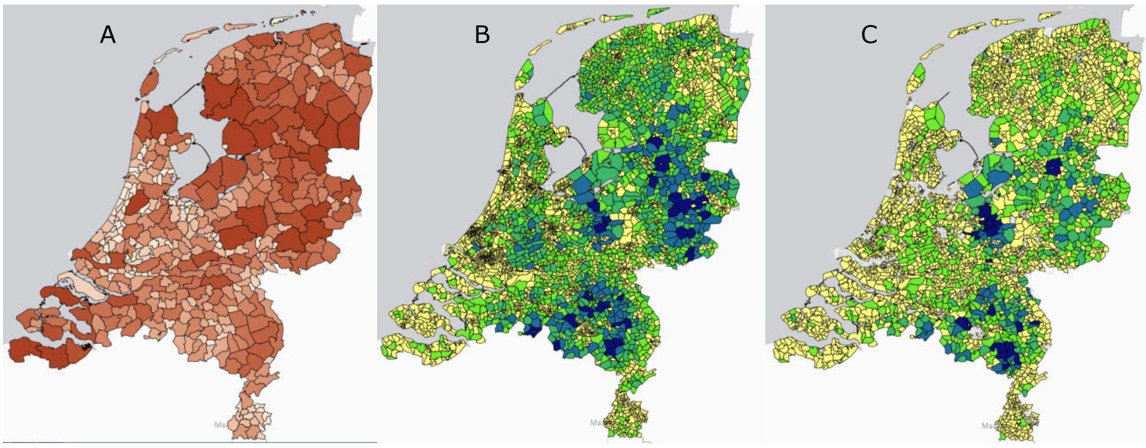


Figure 8. Maps of yearly produced roadside grass clippings (A) [range: 3 to 5,000 tonnes dry weight]; thin manure (B) [range: <10,000 to >150,000 tonnes]; solid manure (C) [range: <2,500 to >30,000 tonnes] with scales from light to dark colour.
Source: www.atlasnatuurlijkkapitaal.nl

Future methods and perspectives

Currently there is no standard method for measuring the circularity or resource efficiency of products or production chains related to residual biomass. However, most residual biomass flows already perform some function in the agricultural cycle. Although preferable to waste, this function is not necessarily the application which creates the highest total value, this value can be according to the value pyramid (Figure 6), or a combination of measures for economic, natural and social capital. Here we would like to briefly discuss some other options for taking circularity into account.

In principle, the circular economy and circularity of a material or product cycle is about reducing losses in order to keep the value of cycle high. These losses are mostly related to pollution of residual biomass flows by hazardous substances that are difficult to separate again, e.g. pesticides or heavy metals in agricultural waste, or to the dilution of unwanted compounds in different environmental compartments, e.g. nitrate is lost to groundwater and phosphate is deposited in sediment. A combination of these problems occurs in communal wastewater, where hazardous chemicals, pathogens and dilution are potential obstacles to the recovery of resources. One way to preserve these resources and keep them available for others to use would be to avoid diluting them and mixing them with unwanted compounds. A way of quantifying this dilution or entropy had been developed as part of linking economic growth to environmental pollution in order to find an optimal balance between the two.[69, 70] For example, different residual biomass flows can be analyzed in terms of the reversibility or entropy of phosphate. In the case of wastewater, household organic waste and sediment dredging, the entropy of phosphate would be mainly related to the chemical state/species in which it is present and the concentration. Household organic waste becomes a good fertilizer after composting, whereas wastewater needs to be treated in order to deposit struvite. Sediment dredging would have to undergo a similar process, but the bound state of phosphate, as well as the lower expected concentration, would complicate this. Further research is needed to assess the functionality of such a method, specifically for application as part of a sustainability assessment.

5.3 Other non-environmental elements and indicators

As previously mentioned, sustainability involves other non-environmental elements related to people, profit, partnership and peace; and to financial capital, produced capital, human capital and social capital. These are also required for sustainable development. For instance, a business plan usually helps assess the economic viability of implementing new techniques to increase resource efficiency and decrease environmental impact. However, a sustainable plan is not limited to economic capital or profit, as profit can also be natural, i.e. an increase in the natural capital that is at a company's disposal. This means that benefits related to other elements of a sustainable business plan should also be considered, such as an increase in social capital and other effects of an increase in prosperity. Because there are many issues to consider and cooperation between stakeholders is needed, an integral approach is required. For policy-makers this means that several ministries or regulatory agencies might need to work together in setting goals and guidelines to support the sustainable use of residual biomass flows.

It is outside the scope of this report to discuss or advise on how an assessment might cover all these elements. However, the non-environmental elements of sustainability cannot be neglected if they are an obstacle to the transition to a more circular use of residual biomass. Such obstacles include public perception, as briefly discussed in Section 2.7. E.g. people are essential to achieving better separation of residual biomass from abiotic residual materials. Furthermore, a global perspective is required for material flows that come from all corners of the globe. Are there negative impacts on the reduction of poverty and hunger or the promotion of good health, education, gender equality, peace, etc. in those countries? Such impacts would not contribute to a sustainable supply chain. Moreover, the economic risks related to the material supply chain and other factors need to be known to the stakeholders involved. The Ellen MacArthur Foundation suggests different complementary indicators related to profit such as: material price variation risk, material supply chain risks, and material scarcity.[7] On a national scale, the Sustainable Development Solutions Network has created an extensive list of indicators that could be used or developed in order to measure progress towards all of the sustainable development goals, including people, prosperity, partnership and peace.[65] But at a more detailed scale, e.g. for a specific production chain, these indicators are not very useful.

Although for specific cases relevant quantitative or qualitative indicators for non-environmental elements can be found, e.g. by expert and stakeholder consultation, standard indicators are rarely available. Often stakeholder consultation on these elements will result in identification of the key issues related to sustainable development and in that way can be addressed.

6 Stakeholder involvement in the transition to a circular economy

In the previous chapters issues related to residual biomass were discussed, from obstacles regarding implementing new loops to methods needed to quantify circularity. To optimize the use of biomass and the up-cycling of residual biomass flows it is important to take into account the supply chain of a product and the stakeholders that are involved. This is the first step in the process and can be done by different methods. Stakeholders have different roles in the supply chain and are influenced by different factors, such as regulations, public opinion and economic perspectives. This chapter presents a system of framing the context and ensuring that the involvement of stakeholders is beneficial.

6.1 Policy, sector and product level

To describe the different roles of stakeholders in a circular economy, a conceptual framework developed by Spijker and van der Grinten,[71] consisting of three levels, is used. Core elements of this approach are the material flows and the boundary conditions determined by current policy and legislation. This approach was adapted from previous models by Hu et al.[72] and Guinee et al.[73] The three levels of stakeholders are the policy level, the sector level and the product level. These levels are briefly described in Table 3.

Table 3: The three levels for Life Cycle Analysis of materials and their scope. Table from Spijker and van der Grinten[71].

Level	Scope
Policy	Regulatory framework and constraints
Sector	Market, material flows, market supply and demand
Product	Products and product criteria

The first level is the policy level, consisting of different local and (inter)national governments. At this level, general policy and its boundary conditions are determined. From this level, general incentives (in the form of legislation) are given towards the two underlying levels.

The second level is the sector level. At this intermediate level, the material flows are situated, which are determined by supply and demand (free market system). At this level, providers of waste streams, processors of waste, resource traders and producers play their respective roles and, ideally, interact with each other.

At the third level, the product level, regulation facilitates the transformation of waste to product (e.g. End of Waste criteria) and technical as well as environmental product criteria are established.

An example of wastewater treatment versus recycling of building materials

Spijker and van der Grinten[71] elaborated this framework for the analysis of material streams from the recycling of building materials and wastewater treatment (Table 4).

At the policy level, the regulatory framework for the waste stream of building materials includes the landfill ban on granulate from building and demolition waste. This gave an incentive to the market (sector level) and interaction between supply and demand developed, resulting in a large proportion of this waste stream (currently 95%) being processed and made suitable for reuse. At the product level, in this case, official End of Waste criteria for concrete granulate from construction and demolition waste are currently in preparation.[74]

The wastewater chain is also developing a range of initiatives to promote reuse, e.g. by recovering phosphate and cellulose from wastewater. However, there are still some obstacles to overcome. For instance, there is no clear policy on the reuse of wastewater (policy level). Until recently, policy for wastewater treatment has been focused on water quality. There are no policy measures in place to promote the reuse of wastewater. While trade and industry determine the processes at the second level for building materials, for the wastewater stream, government organizations (municipalities, water boards) are still the main actors at this level. This can partly be explained by the difference in phase of development of the two waste streams, since the reuse of resources from wastewater has only recently become a focal point. This has been picked up by the water boards, which have initiated a range of research projects on the possibilities of reuse. However, trade and industry (demand) do not play a significant role at this level yet. One of the reasons for this is that it is not yet clear what products (supply) can be manufactured from wastewater (product level). This makes it more difficult to draw up End of Waste criteria. There is one exception: recovered phosphate (e.g. struvite), has recently been added to the Dutch Decree implementing the Fertilizer Act, allowing the use of struvite as fertilizer and opening a market for this resource.

Table 4. Schematic overview of the three levels of stakeholders applied to granulate from the recycling of building materials and sludge from wastewater treatment.
Source: Spijker and van der Grinten [71] (translated)

Level	**Case: building materials**		**Case: wastewater (sludge)**	
Policy	Landfill ban on stone construction and demolition waste Ambition in the Dutch Waste Management Plan		Water quality/quantity as starting point	
Sector	Chain:	Construction and demolition waste: companies (demolition, recycling, buyers)	Chain:	(Waste)water treatment: companies, municipalities, water boards
	Knowledge:	Companies and branch organizations	Knowledge:	STOWA, institutes
	Value:	Increase in each step of the value chain	Value:	No clear development yet
Product	EoW:	Stone construction and demolition waste	EoW:	Based on use as a resource / manure / (generation of energy)
	Criteria:	Regulation on granulate from recycling of building materials, Soil Quality Decree	Criteria:	Dutch manure law

6.2 Framework

By choosing a set of indicators and system boundaries when conducting an LCA, a lot of implicit choices are made related to the goals and scope of a sustainability assessment. This has often led to disappointment in the outcome of studies where the selection of such indicators was not based on an informed decision.[75] As a thorough sustainability assessment, such as a LCA, is often data-intensive and time-consuming, it is deemed better to adopt a tiered approach as part of a wider assessment framework (see Figure 9).[76] The first tier is the determination of the conditions to be taken into account for the sustainability assessment based on consultation between stakeholders. The second tier is in theory optional: an initial screening of the sustainability optimization, upon evaluation continuing to a more thorough assessment (Tier 3). This is not only a theoretical methodology; practical methods and guidelines are being developed for each tier. This will be applied to the wastewater case, as described chapter 4; the results of this exercise will be published separately.

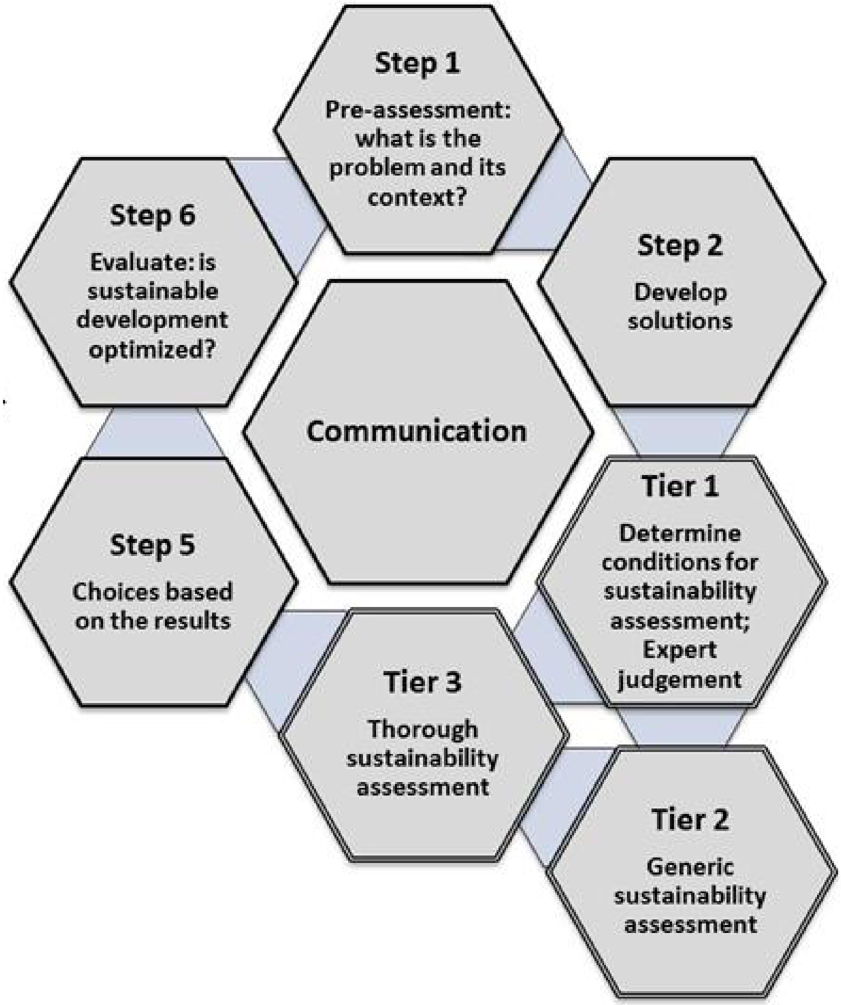


Figure 9. The Solution-focused Sustainability Assessment framework, including the tiered identification key for a better fit of the assessment with the intended optimization
Source: Zijp et al.[76]

7 Conclusions and recommendations

The previous chapters presented various issues related to residual biomass use and discussed obstacles for increasing circularity of residual biomass related loops. Although common sense and specific case studies have been shown to result in several good ideas for increasing use of residual biomass and increasing circularity, the growing interest in new applications requires a more systematic and standardized method for including circularity in a sustainability assessment. Here we present an overview of our conclusions and recommendations on the basis of the foregoing analysis with a focus on finding optimal use scenarios to increase circularity.

7.1 Conclusions

The main points that emerge from the analyses related to the optimization of sustainable residual biomass use are as follows:

1. New applications for residual biomass often involve changing existing loops (e.g. plant meal used for extracting proteins for food instead of improving soil fertility). The concern here is that ‘changing use scenarios’ may have undesirable side effects. The main cause for this concern is the reduced residual biomass availability for the original, (also) valuable use scenario. This means that for finding the optimal application the assessment should consider changes in resource use and losses. However, changes in environmental impacts and potential risks (e.g. of chemical contaminants or pathogens) and the yield of the production process should also be considered. The new application should be compared with the existing one to evaluate optimization.
2. Currently, choosing residual biomass applications are guided by principles such as reducing cost, cascading (with energy production as the lowest-value option) and reducing environmental impact. Most use scenarios are currently based on a goal related to one specific principle. For example, a high-grade application (following the cascade pyramid) or the reduction of GHG emissions (lowering environmental impact). An evaluation with a broader set of metrics is warranted, and can be based on a LCA approach, including tools like NTA 8080 and the Agricultural Cycle Test.
3. In the current situation, regulations on chemical safety (e.g. REACH) and waste management (e.g. Waste Framework directive) protect people and the environment, but the use of these fundamental, first-tier approaches, designed to handle potential threats, may prohibit the design of more sustainable loops. Although End of Waste regulation aims to facilitate safe reuse in more sustainable applications, conflicts between regulations form a current barrier for new residual biomass applications. Sometimes, methods are in place for evaluating risks. For example, in the specific use scenario of residual biomass as soil fertilizer after application as co-digestate, there is a standardized method for assessing the environmental risks of

chemical contaminants. Other use scenarios do not have such a method for safety assessment available, which hinders the successful evaluation of potentially more optimal use scenarios.

4. Assessing the sustainability of residual biomass loops requires various types of indicator to be considered, as listed below:
    a. Impact indicators: Indicators of the environmental impact of a new residual biomass application. Several methods, such as ReCiPe, PEF and NTA 8080, have well defined and daily-use-oriented indicators for environmental impact.
    b. Resource indicators: Indicators of resource use and losses in a residual biomass loop. Essentially the aim of reducing resource losses is directly related to 'closing a loop'.
    c. Yield indicators (multi-criteria): A benefit assessment of the yield in terms of natural, economic and social capital resulting from a new residual biomass application. This yield should be taken into account in relation to the environmental impact and resource use and loss.
5. Approaches to optimizing residual biomass use include:
    a. Comparing different use scenario options in terms of sustainability metrics, as mentioned above, and including an assessment of the transition of existing residual biomass use scenarios to (more sustainable) alternatives.
    b. Putting these scenarios in perspective of the practical situation, by exploring the requirements, goals and limitations imposed by different stakeholders at the Policy, Sector and Product level. In this way, the boundaries of a use scenario can be defined. These might be limits dictated by national or European regulations on safety (Policy level), quantitative limits on material flows at the Sector level or technical product criteria (Product level).
    c. Making a selection of indicators and methods for assessing the sustainability of different use scenarios relevant to the stakeholder perspectives. Such a selection can vary, e.g. by location, spatial scale, product or residual biomass flow.

7.2 From conclusions to recommendations

The analysis presented in the previous section provides the outline of a system approach to the transition to sustainable circular residual biomass use. The outline consists of a combination of the indicators and methods currently available for the sustainability assessment of residual biomass flows and an approach to weight these based on relevant goals and limitations. It is recommended that such a system becomes part of any framework for assessing the sustainability of residual biomass applications. Such a framework is recommended to implement this system in a tiered way so that the appropriate balance is found between the complexity of an assessment and the benefits to be gained. Below we will discuss recommendations for the indicator system and method, as part of a sustainability assessment, needed for finding the optimal residual biomass application. Such a system needs to be adjusted to then needs of the transition to a circular economy.

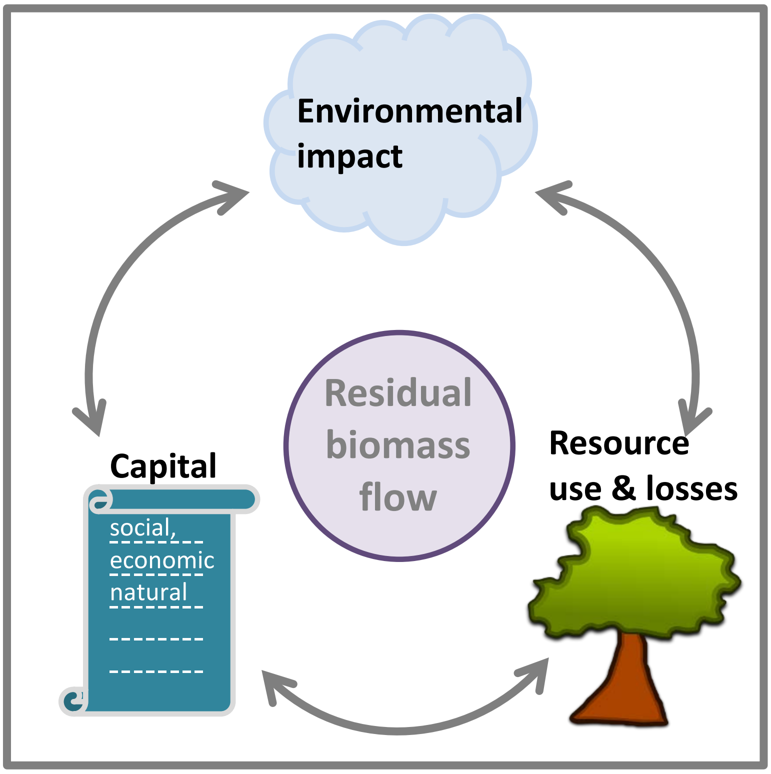


Figure 10. Indicators and methods system for assessing the sustainability and circularity of residual biomass flows as part of the circular economy. Three types of indicator are needed for (i) environmental impact, (ii) resource use and losses, and (iii) yield in terms of social, economic and natural capital. The combination of these three indicators indicates the degree of circularity.

Indicator system

When considering the assessment of the sustainability as part of the circular economy, we recommend the design and implementation of a versatile system of indicators. From the review of the existing methods for assessing the sustainability of residual biomass flows in this report, it becomes clear that three types of indicator are needed: (i) an environmental impact indicator, (ii) an indicator of resource use and losses, and (iii) an indicator of the yield in social, economic and natural capital of a loop (Figure 10). The capital yield is the degree of increase in value of the environmental, economic and social systems that will result from the proposed application for residual biomass use.

Further development of a methodology for combining these three types of indicator is required for assessing the degree of circularity of a residual biomass flow. Although several methods already partially combine several indicators, they still lack standard options for combining all three aspects. Additionally, it is recommended to further develop individual indicators for each element of sustainability, which are far from complete in most methods. For example, indicators related to soil quality, resource losses and economic and natural capital.

Because assessing the sustainability of a residual biomass flow should be done as objectively as possible, it is recommended to extend or build upon existing standardized methods (e.g. ReCiPe or NTA 8080).

In general, where a metric is missing but is seen as important, it should be developed. Where some metrics are present but complex to use, it is recommended that simpler, more practical, methods be devised. For example, a European test trajectory is currently developing Product Environmental Footprint approaches, which can be seen as a derivative of (the often more comprehensive) Life Cycle Assessment approaches.

It is recommended that – by virtue of some specific elements of the residual biomass loops – efforts are undertaken to help (further) operationalize a system of indicators with which sustainable development options can be compared and weighted. For example, an appropriate circularity indicator would be a logical summary metric when the goal is a transition to a circular economy.

It is recommended to create a sustainable development weighting system not only at the most complex scientific levels in the definition of indicators, but also at a practical level. It is also recommended to develop a tiered approach (simple when possible, complex when necessary), which will allow, for example, alternative options to be rapidly evaluated.

Optimization
The most sustainable resource use does not result from only assessing the degree of sustainability of a residual biomass application. For this, different options or scenarios need to be compared and weighed in order to find the most sustainable one (Figure 11). Additionally, the applications need to fit the system boundaries such as limits regarding safety and stakeholder goals (e.g. profitability or relative reduction in environmental impact).

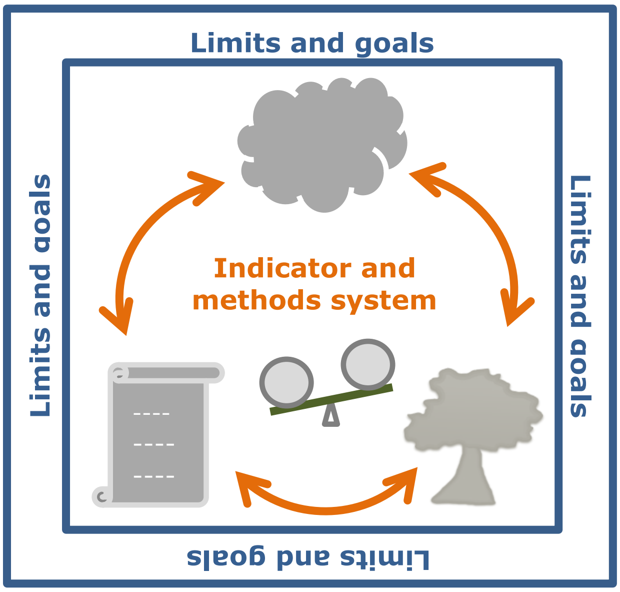


Figure 11. The two requirements for assessing progress towards a circular economy. Its limits and goals, such as GHG emission limits or resource efficiency goals, make up the boundary conditions within which both existing and new applications should fit. This is assessed using an indicator and methods system (Figure 10).

This leads to following recommendations:

- Take into account the indirect effects of changes in residual biomass flows to an alternative use scenario. Alternative scenarios aim to improve the cascade of residual biomass use, in order to increase the total value of its capital, in terms of natural, economic and social capital. However, the gain or cost in terms of natural capital is currently seldom taken into account when considering alternative residual biomass applications. For policy-makers it is important to understand the effect of alternative uses on natural, economic and social capital.
- Carefully select relevant indicators and methods in order to meet the optimization goals set by the (different) stakeholders. These indicators should fit in a framework, which helps decision-making, based on the current goals for which useful indicators or methods should be selected. This links to the recommendation of developing a versatile set of indicators, but these should also vary from simple to complex, e.g. screening level or qualitative to quantitative.
- Identify and take into account the boundary conditions of the options being assessed. These can be relatively well known, such as existing regulations or the availability of a residual biomass flow. However, existing regulations might be a limiting factor, especially when they were designed as 'a safe standard under all circumstances'. In that case an adaption or an exception might be possible based on evaluation of a use scenario. One possibility to make such an exception is by defining End of Waste criteria. However, these criteria should comply with legal conditions regarding acceptable risk. In the next section, we will discuss the possibilities for doing so as this is often an obstacle due to uncertainty related to the unknown.

Safety assessment

In a developing circular economy there will be an increase in the use of resources from waste streams via new applications, asking for decisions about End of Waste. For this reason it is essential that End of Waste criteria are developed that guarantee human health and environmental safety. However, the lack of information on e.g. the content of hazardous substances or pathogens and their environmental or human health effects makes it difficult to determine such criteria. As a first step towards the safe use of residual flows, a checklist should be developed in order to decide what type of additional information is needed for a more detailed assessment of the environmental and human health risks. This is closely linked to what would be needed to provide End of Waste criteria for residual biomass flows.

On the basis of the limited analysis of the risks regarding pathogens and chemical contaminants of residual biomass flows in Chapter 3, this safety checklist could consist of four categories: related to the content, origin, production process and intended use of the residual biomass flow, see Table 5. It is recommended to further develop a safety assessment for different levels of technological development in order to stimulate innovation. At the last stage of development the assessment should provide adequate information to derive End of Waste criteria.

Table 5. Aspects of a risk evaluation checklist for residual biomass based on the risk analysis in Chapter 3

Category	**Relation to potential risk**
Content	If the contents of a residual biomass flow are known with little uncertainty, the potential risks should be assessed on this basis. Often, however, the contents are unknown or known only with considerable uncertainty.
Origin	Mixed flows lead to higher (potential) risks and usually greater uncertainty as to presence of contaminants. Flows that consist of animal or human waste have a much higher potential for contamination by pathogens and medication. Plant diseases and mould might also need to be considered.
Production process	The use of plant protection agents and other chemicals in cultivation or production can lead to higher risks for the residual biomass flow. The location of contaminated soil and water sources should be considered. Sanitization can reduce risks.
Intended use	Increased spreading and exposure of potential contaminants needs to be considered. Their introduction into the food production cycle is a potential risk. If the application is linked to increased transportation, this can lead to unwanted exposure at new locations and further spreading of contaminants.

Overall recommendation

In general, more than just qualitative recommendations are needed to improve on the current situation. Therefore, it is recommended to develop test cases, to which the main points of the above recommendations (indicator system, optimization, safety assessment) are applied. These could use e.g. a national mass-balance analysis to identify ‘main drivers’ of non-sustainable practices or a more detailed analysis of specific residual biomass applications or cycles.

Although the focus of this report was residual biomass, a sustainability assessment can be applied to full biomass loops, including residual biomass, in order to establish a symbiosis between biomass use scenarios instead of only finding the optimal use scenario for a specific residual biomass flow as it becomes available. This requires a more active approach to optimization, but this further optimization of biomass resource flows can use the same systems analysis using sustainability metrics and system boundaries (Figures 10 and 11).

8 Acknowledgements

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9 Appendices

9.1 Appendix A: Overview of existing sustainability indicators

	Dutch Building Decree[52]	**NTA 8080**[37, 78]	**EU Resource Efficiency Scoreboard 2014**[8]	**Agricultural Cycle Test**[51]	**Product or Organizational Environment Footprint**[62]	**Ellen MacArthur Foundation Circularity Indicator**[7]
Application domain	**Building materials and products**	**Biomass and residual biomass**	**EU resource efficiency**	**Agriculture and food consumption**	**Product and organization**	**Technical cycles and non-renewable materials**
Reuse and recyclability	• Components for reuse, Materials for recycling, Materials for energy recovery, Exported energy		• Recycling rate of municipal waste • Recycling rate of e-waste			• Material collected for recycling • Recycled feedstock • Components collected for reuse • Reused components
Waste	• Hazardous waste • Radioactive waste • Non-hazardous waste		• Generation of waste excluding major mineral wastes • Landfill rate of waste excluding major mineral wastes • Eco-Innovation Index	• Losses: – Nitrogen – Phosphate – Organic carbon		• Material going to landfill/energy recovery • Waste from recycling process
Durability	• Reference service life • Maintenance • Repairs • Replacement • Refurbishment					Lifetime and functional units compared to industry average (utility) considered during use

	Dutch Building Decree[52]	NTA 8080[37, 78]	EU Resource Efficiency Scoreboard 2014[8]	Agricultural Cycle Test[51]	Product or Organizational Environment Footprint[62]	Ellen MacArthur Foundation Circularity Indicator[7]
Resource use	• Use of renewable primary energy resources as raw materials • Total use of renewable primary energy resources (primary energy and primary energy resources used as raw materials) • Use of non-renewable primary energy, excluding non-renewable primary energy resources, as raw materials • Use of non-renewable primary energy resources as raw materials • Total use of non-renewable primary energy resources (primary energy and primary energy resources used as raw materials) • Use of secondary material • Use of renewable secondary fuels • Use of non-renewable secondary fuels • Net use of fresh water • Usage can be specified, e.g. due to transport: fuel type and consumption of vehicle or vehicle type used for transport…	• Competition with food and local applications of biomass – The production of biomass for energy must not endanger the food supply and local biomass applications (energy supply, medicines, building materials).	• Domestic material consumption per capita • Built-up artificial land • Productivity of artificial land • Water exploitation index • Water productivity • Energy productivity • Energy dependence • Share of renewable energy in gross final energy consumption • Eco-Innovation Index		• Resource depletion – water • Resource depletion – mineral and fossil fuels	• Virgin feedstock

	Dutch Building Decree[52]	**NTA 8080**[37, 78]	**EU Resource Efficiency Scoreboard 2014**[8]	**Agricultural Cycle Test**[51]	**Product or Organizational Environment Footprint**[62]	**Ellen MacArthur Foundation Circularity Indicator**[7]
Human or environmental impact	• Human toxicity potential, terrestrial and aquatic ecotoxicity potential, global warming (GHG), ozone depletion, acidification potential for soil and water, eutrophication potential, photochemical ozone creation potential • Depletion of abiotic resources: elements, • Depletion of abiotic resources: fossil fuels	• GHG emissions – The greenhouse gas balance of the production chain and application of the biomass must be positive. – Biomass production must not be at the expense of major carbon sinks in the vegetation and in the soil. • Biodiversity – Biomass production must not affect protected or vulnerable biodiversity and must, where possible, strengthen biodiversity. • Environment – In the production and processing of	• GHG emissions per capita • Biodiversity – Index of common farmland bird species – Area under organic farming – Landscape fragmentation • Air quality – Urban population exposure to air pollution by particulate matter – PM2.5 and PM10 – Urban population exposed to PM10 concentrations exceeding the daily limit value (50 µg/m3 on more than 35 days per year) • Land and soils – Soil erosion by water – area eroded by more than 10 tonnes per ha per year – Gross nutrient balance in agricultural land – Gross nutrient	• Soil – Heavy metals, Soil biodiversity • Climate – CO_2, N_2O, CH_4 • Water quality – N, P • Biodiversity • Local environment – Transport – Health, smell • Land use	• Climate change – (GHG?) – Ozone depletion – Human toxicity: cancer effects – Human toxicity: non-cancer effects – Particulate matter/ respiratory inorganics – Ionizing radiation – Photochemical ozone formation – Aacidifica-tion – Eutrophication: terrestrial – Eutrophication: aquatic – Ecotoxicity: freshwater aquatic • Land use	• Toxicity (e.g. REACH, C2C certified banned list of chemicals) • Energy usage and CO_2 emissions (LCA) • Water footprint

	Dutch Building Decree[52]	**NTA 8080**[37, 78]	**EU Resource Efficiency Scoreboard 2014**[8]	**Agricultural Cycle Test**[51]	**Product or Organizational Environment Footprint**[62]	**Ellen MacArthur Foundation Circularity Indicator**[7]
		biomass, the soil and soil quality must be retained or even improved. – In the production and processing of biomass, ground and surface water must not be depleted and water quality must be maintained or improved. – In the production and processing of biomass the air quality must be maintained or improved.	balance in agricultural land: nitrogen – Gross nutrient balance in agricultural land: phosphorus			

	Dutch Building Decree[52]	**NTA 8080**[37, 78]	**EU Resource Efficiency Scoreboard 2014**[8]	**Agricultural Cycle Test**[51]	**Product or Organizational Environment Footprint**[62]	**Ellen MacArthur Foundation Circularity Indicator**[7]
Circularity or resource efficiency			• Resource productivity			• Material Circularity Indicator
Other		• Prosperity – The production of biomass must contribute towards local prosperity. Social well-being – The production of biomass must contribute towards the social well-being of the employees and the local population.	• Addressing food – Daily calorie supply per capita by source • Ensuring eff. mobility – Average CO_2 emissions per km from new passenger cars – Pollutant emissions from transport – NOx, NMVOC and PM10 – Modal split of passenger transport – Modal split of freight transport • Improving buildings – Final energy consumption in households – Final energy consumption in households by fuel			• Material price variation risk • Material supply chain risks • Material scarcity • Service and performance models

9.2 Appendix B: List of residual biomass flows categorized as primary or non-primary

Primary residual biomass flows
Bark
Other fresh wood: branches, tops and low-value spindle wood originating from forests and nature reserves managed with an eye to preserving their function for the long term; or on behalf of changes to functions for which permits have been granted; stumps
Straw: a mixture of straw, barley straw, wheat straw, rice stalk, hemp and other straws
Residual products (shells): a mixture of cocoa shells, peanut shells, nuts, including walnut and almond shells, rice husks and other shells
Horticultural waste
Fruit farming
Peeling waste from flower bulbs
Agricultural waste
Non-primary residual biomass flows
Prunings (parks and public gardens)
Sawdust
Other fresh wood: branches, tops and low-value spindle wood originating from gardens, parks and public gardens; branches, tops and low-value spindle wood originating from conversions other than those of forests and nature reserves on behalf of changes to functions for which permits have been granted; residues that are produced when round timber is sawn and processed
Processed wood A: untreated a mixture of cork and other untreated wood
Processed wood B: painted/glued wood a mixture of panel materials and other painted/glued wood
Processed wood C: impregnated wood a mixture of impregnated, impregnated wood: heavy metals, impregnated wood: halogenated organic compounds, impregnated wood: non-halogenated organic compounds and other impregnated wood
Wood from processing a mixture of wood from composting, wood from fermentation, wood that has been in the water for a long time and other wood from processing
Roadside grass
Other grass grass and cuttings (including from waterways and reeds) that originate from maintenance activities; this does not include agricultural grass
Auction waste

Manure
  - a mixture of poultry manure, cow manure, pig manure, horse manure, processed manure from manure fermentation (digestate), processed manure from co-fermentation with manure (digestate), processed manure from other processing and other manure

Sludge
  - a mixture of industrial sludge, sludge from sewage/wastewater treatment plants, sludge from sewers, cesspits and pumping stations, sludge from preparation of drinking water, paper sludge and other sludge

Potato peel
Rice husks
Other skins/husks/stones
Moist fibre/wet mash
Coffee pulp
Used cooking fats and oils
Soft drinks and light alcoholic spirits unsuitable for human consumption
Dairy products unsuitable for human consumption
Foodstuffs unsuitable for human consumption
Slaughter waste
Glycerine – glycol (biodiesel production) as far as it concerns crude glycerine (glycerine that is not refined)
Black liquor:
  - chemically treated wood that comes into existence during the production of paper. It is a mixture of chemicals and dissolved wood material that remains after boiling in sulphate.

Organic waste from households and companies (trading, services, other)
Mixture of combined flows
  - organic wet fraction that is released when sorting industrial waste, domestic waste, etc. and is considered a combined waste

a. List from The Netherlands Norm Institute according to NTA 8003:2008.

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