System Initiative on Environment and Natural Resource Security

Project MainStream
Urban Biocycles

In Collaboration with the Ellen MacArthur Foundation

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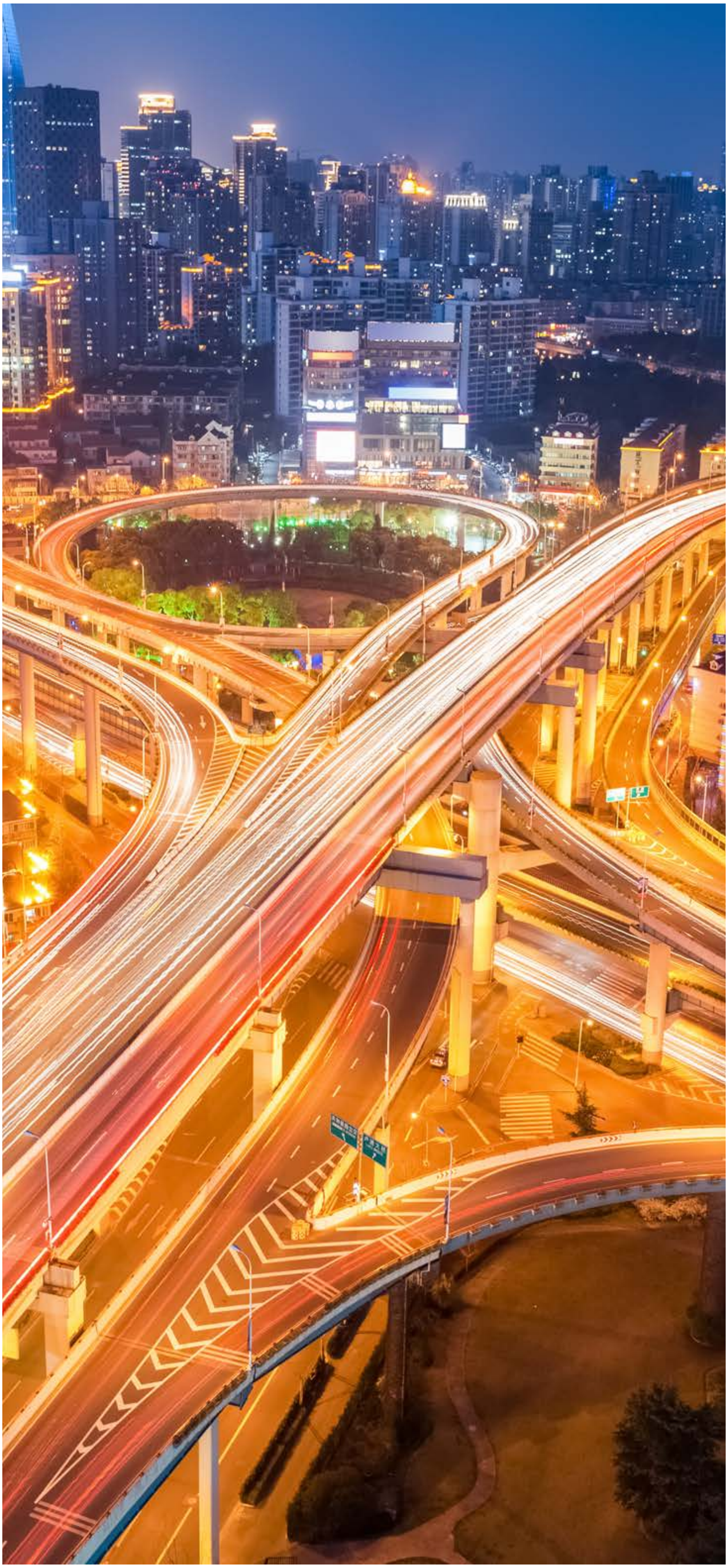

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Foreword

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Cities are places of ingenuity and delight, as well as engines of economic growth and opportunity. However, they are also great concentrators of materials, insatiable consumers of resources and responsible for 75% of global carbon emissions. Even now, many of our cities are struggling to cope with the demands of large populations and a wide-ranging ecological impact. Each year the global urban population swells by a number equivalent to the population of the United Kingdom, with most of this growth occurring in emerging economies with poor or inadequate infrastructure. Confronted with this challenge, we are compelled to rethink the relationship between cities and the resources needed to allow them to function effectively.

This report on the Urban Biocycle represents a clear and coherent response to the challenges facing cities today. The solutions identified could transform the vast and growing volumes of organic "waste" flowing through our cities into valuable resources. These solutions are circular, in that they focus on closing the loop between food production, urban activity and soil; they capture untapped value and foster effective systems that eliminate negative externalities, such as greenhouse gases. They are concrete in that the technologies proposed exist today. Finally, the study is collaborative, in that it harnesses the convening power of the World Economic Forum, the circular economy expertise of the Ellen MacArthur Foundation and the industry insights of Project MainStream companies.

A past effort of Project MainStream, The New Plastics Economy, has now gathered enough momentum to become a self-sustaining global initiative with the ambition of radically transforming the plastics industry. It is hoped that this report, in a similar way, will lay the foundation to a blossoming of new thinking and activity transforming the concept of "organic waste" into a thriving biocycle economy. What is needed now is to build upon the opportunities touched on in this publication, leveraging the power of public-private partnerships to overcome the systemic stalemates that stand in the way and to scale up solutions in cities around the globe.

Project MainStream

The World Economic Forum and the Ellen MacArthur Foundation launched Project MainStream in 2014, a multi-industry, global initiative that serves as the umbrella for this report. The project is led by the chief executive officers of seven global companies: Averda, Tarkett, Royal DSM, Ecolab, Philips, SUEZ and Veolia.

Project MainStream aims to accelerate business-driven innovations and help scale the circular economy (building awareness of it, and increasing impact and implementation). It focuses on systemic stalemates in global material flows that are too big or too complex for an individual business, city or government to overcome alone, as well as on enablers of the circular economy, such as digital technologies.

Disclaimer

This report was produced by a team from the Ellen MacArthur Foundation, which takes full responsibility for the report's contents and conclusions. While the project participants and experts consulted have provided significant input to the development of this report, their participation does not necessarily imply endorsement of its contents or conclusions.

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Executive Summary

This report focuses on the potential of the significant volume of organic waste flowing through the urban environment. The aim is to highlight the opportunities to capture value, in the form of the energy, nutrients and materials embedded in these flows, through the application of circular economy principles. Organic waste – from the organic fraction of municipal solid waste streams and wastewater that flows through sewage systems – is traditionally seen as a costly "problem" in economic and environmental terms. This report will explore the idea that the equation can be reversed by designing more effective recovery and processing systems to turn organic waste into a source of value and contribute to restoring natural capital.

Every year, people harvest roughly 13 billion tonnes of biomass globally for food, energy and material purposes. These materials flow through the sector of the economy called the "biocycle economy", as it is referred to in this report. It includes industries that deal with biological materials at different stages of the value chain: for example, agriculture, forestry and fishing at the primary stages; food processing, textile manufacturing and biotechnology in the processing stages; and retail and resource management in the consumption stage. Together, they generate an approximate global value of $12.5 trillion, equivalent to 17% of global gross domestic product (GDP) in 2013.

Moreover, the biocycle economy's share of the overall economy is much larger in emerging economies, where the majority of growth is expected with an expanding world population. This will lead to rising per-capita consumption. In this context, the volume of biomass flowing through the global economy is set to grow; and notably, global demand for food is expected to rise by about 55% by 2050.

While such parameters offer considerable opportunities, they also involve numerous challenges. These include significant structural waste in the biocycle economy (about a third of all food produced globally is lost or wasted), as well as natural capital losses and negative environmental externalities. If food waste were a country, it would be the third-largest emitter of greenhouse gases (GHGs) in the world. Land degradation affects roughly one-quarter of land globally and costs $40 billion per year,[1] and eutrophication, or the accumulation of nutrients and resulting overgrowth of plant life caused by surface run-off, has created aquatic dead zones all around the world.

At the same time, the economic opportunities are significant. The World Economic Forum estimates that potential global revenues from the biomass value chain – comprising the production of agricultural inputs, biomass trading and biorefinery outputs – could be as high as $295 billion by 2020.

Cities, the new powerhouses already generating over 80% of global GDP, will play a major role in addressing challenges and realizing opportunities in the biocycle economy. As major concentrators of materials and nutrients, cities aggregate inputs such as food from rural areas into a concentrated urban space. Today, almost none of these materials are looped back into the biosphere, meaning that rural soils are becoming degraded and relying increasingly on synthetic fertilizers. Cities currently produce about 1.3 billion tonnes of solid waste per year, roughly half of which is organic. This figure is expected to almost double by 2025, with 70% of the total likely to be generated in emerging markets.

A recent study[2] estimated that processing streams of residual organic waste in Amsterdam, the Netherlands, could lead to added value of €150 million, as well as 900,000 tons of material savings and a reduction of 600,000 tonnes in CO_2 emissions annually for the city. Biorefineries, waste separation and return logistics, cascading organic flows and nutrient recovery could be used to generate these benefits.

Some cities have implemented programmes to recover and valorize organic materials, such as those found in food waste and wastewater streams. The volumes of recovered material vary greatly. Milan, Italy now has high rates of recovery, which it uses to generate revenue by producing energy and compost, the decayed organic material used as a fertilizer. Many cities, however, are achieving only low levels of recovery, representing a notable lost opportunity as well as impacting human and environmental health.

Significant opportunity exists to use organic waste material to manufacture a range of products and materials traditionally derived from fossil sources. Biorefineries could be a central technology in this, as they use both solid waste and wastewater as feedstocks. Operating in a similar way to petrochemical refineries, they employ a range of techniques, such as thermal treatment, biological processes and enzymatic conversions, to transform organic feedstock into valuable chemicals and products. Biorefineries have many feedstock options available. The options are categorized as first generation (food-based) and second generation (non-food-based), with the latter being particularly attractive by complementing food production rather than competing with it.

The technology is rapidly evolving. As it matures, biorefineries will produce more and more complex chemicals and materials, with succinic acid and polylactic acid already examples of this (both are useful precursors). It is increasingly evident that organic waste can be used to produce competitive alternatives to resources derived from fossil fuels.

Producing concentrated nitrogen, phosphorus and potassium (NPK) fertilizers is one way of recovering nutrients from organic waste streams, as is using biosolids as compost. Nutrient recovery is attractive as a source of revenue and, importantly, as a guarantee that ecosystems are able to regenerate themselves. Currently, nutrients extracted from soil in rural areas converge towards cities, get consumed and then discharged into places where they accumulate and create imbalances, rather than being returned to the soil. In theory, NPK nutrients recovered from food, animal and human waste streams on a global scale could contribute nearly 2.7 times the nutrients contained within current volumes of chemical fertilizer.[3]

Energy recovery from organic waste can offset operational costs, generate revenue, increase the share of renewables in the energy mix and reduce GHG emissions. The European Commission estimates that biomass energy could meet up to 2% of its overall energy target. Anaerobic digestion is the most widely adopted technology in this area and can be applied to a wide range of organic materials to generate biogas, leaving a nutrient-rich substance called digestate. The biogas can be either fed to the gas grid or converted to electricity using conventional thermal-power processes. Recovering energy in the wastewater sector is attractive, as it can offset the energy required for treatment. In the best example of this, a plant in Denmark has managed to produce more electricity than it requires for its operations, making it a net exporter of power.

Several barriers need to be overcome to shift the system towards one aligned with circular principles. These include regulatory barriers, such as inconsistent and ill-fitting definitions of waste, and economic hurdles, not least of which is the accurate pricing of externalities that tilt the field towards incumbent systems, rather than levelling it for biologically derived materials and energy. Overcoming such barriers will further enable the technological advances required to realize such opportunities.

Clearly, the high-level opportunity is there to capture greater value and increase the contribution of urban biocycle materials towards building natural capital. However, this report demonstrates the need for further analysis. What is required is no less than the following: to develop the baseline understanding of the urban organic landscape as well as quantify the opportunity; to quantify the private-sector opportunities; to identify the systems solutions that enable economic post-use nutrient capture; and finally, to highlight the regulatory levers for developing markets and capturing value.

The Biocycle Economy

A circular economy's overarching framework distinguishes between two cycles of materials: biological and technical.

Biological cycles contain those materials that can safely cycle in and out of the biosphere. The materials include food, fibres and bio-based construction materials, such as wood. Technical cycles, on the other hand, contain flows of materials that cannot be appropriately returned to the biosphere, such as plastics and metals found in myriad products, from engines to washing machines to mobile phones.

The biocycle economy refers to those industries dealing with biological cycles. Such industries include agriculture, forestry and fishing at the primary stages of the value chain; food processing, textile manufacturing and biotechnology in the processing stages; and retail and resource management in the consumption and end-of-use stages.

Compared with the technical cycle, the opportunities for shifting towards a circular model, and the mechanisms for doing so, have so far been largely unexplored in the biocycle economy.

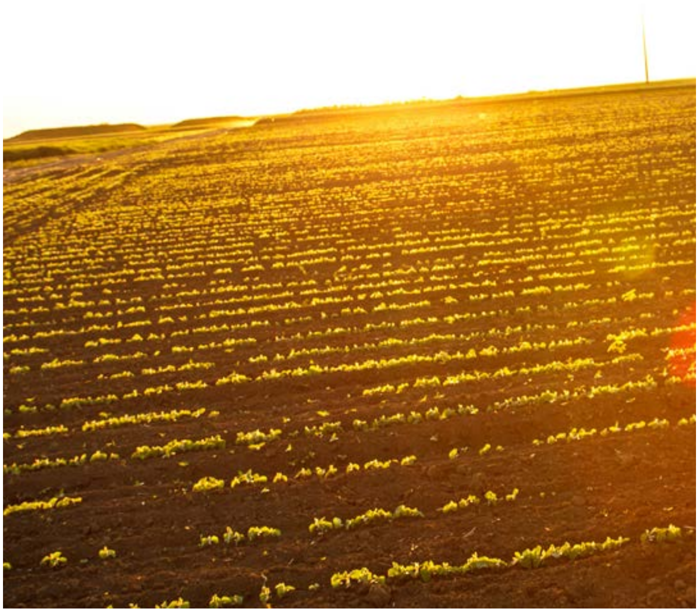
Context Setting

Understanding the biocycle economy is crucial because it plays a critical role in global economic, human and environmental systems. According to the Natural Capital Coalition, "farmers, traders, wholesalers, food manufacturing companies, and retailers together make up the world's largest sector, generating an approximate global value of around USD 12.5 trillion based on revenue, or 17% of world gross domestic product (GDP) in 2013".[4] In emerging countries, the biocycle economy's proportion of the overall economy is even more significant; for example, the agricultural industry, including crops and livestock, accounts for as much as 22% of Brazil's GDP.[5]

The coming decades will present significant challenges, largely because of the entrenched linear model that has dominated the global economy since the Industrial Revolution. Global demand for food is expected to grow by about 70% between 2005 and 2050, increasing the pressure on the availability of land.[6] The growing demand for new biological feedstocks to supply a variety of uses, including biofuels, biomaterials and pharmaceuticals, will stiffen competition for land. Moreover, the effects of climate change on soil quality and land productivity will further exacerbate such challenges.

Additionally, significant structural waste, natural capital losses and environmental externalities in the current biocycle economy need to be addressed:

- Agricultural activities account for almost 70% of global water withdrawals.[7]
- About a third of all food produced globally, worth roughly $680 billion in high-income countries and $310 billion in emerging countries, is lost or wasted each year.[8] If food waste were a country, it would be the third-largest emitter of greenhouse gases (GHGs).
- Land degradation affects roughly one-quarter of the global land surface; about 75 billion tons of fertile topsoil are lost each year, with estimated annual losses amounting to $490 billion.[9]
- Mismanagement and disruption of nutrient flows within natural systems – for example, nutrient cycles and carbon cycles, and the use of pesticides, herbicides and fungicides – lead to externalities such as eutrophication, the accumulation of nutrients and resulting overgrowth of plant life caused by surface run-off. This can result in ocean dead zones, which now affect 240,000 km2, or an area roughly the size of the United Kingdom.[10]
- Externalities from the technical cycle, such as toxins from plastics leaking into oceans, and air and land pollution from industrial activity, cause significant damage to natural ecosystems.



Biomass and Nutrient Flows

Each year, societies harvest roughly 13 billion tonnes of biomass globally for food, energy and material purposes. Food, including biomass produced for animal feed, dominates this material, accounting for about 82%, or 11 billion tonnes, of total extracted biomass. This is followed by bioenergy (11%) and materials (7%).[11] Marine fisheries contribute a further 110 million tonnes to the food supply every year.[12]

Definition of Biomass

"The biodegradable fraction of products, waste and residues from biological origin from agriculture (including vegetal and animal substances), forestry and related industries including fisheries and aquaculture, as well as the biodegradable fraction of industrial and municipal waste; it includes bioliquids and biofuels."[i]

[i] EUR-Lex.

The focus of this report is on the biomass and nutrient flows within cities, and the potential opportunities to increase nutrient recovery and valorize biomass by applying circular economy principles.

Recovery of Urban Organics

Cities are concentrators of materials and nutrients; they aggregate inputs, such as food, from rural areas into a concentrated urban space, returning little of those materials to the agricultural system. Cities consume 75% of the world's natural resources and 80% of global energy supplies, and produce approximately 75% of global carbon emissions.[13] As of 2012, cities produced about 1.3 billion tonnes of solid waste globally per year, a figure expected to grow nearly 70% to 2.2 billion tonnes per year by 2025, with 70% of that waste likely to be generated in emerging markets.[14]

Organic material makes up the largest proportion, or 46% by mass, of municipal solid waste (MSW). This percentage varies around the globe, and is generally higher in low-income countries (64%) compared with high-income countries (28%). However, although the fraction of organic waste may be lower in high-income countries, the absolute volumes can be larger. For example, in countries of the Organisation for Economic Co-operation and Development (OECD), the organic fraction of MSW is estimated to be 27%, but because these countries generate 44% of the world's total MSW, their absolute quantity of organic waste is larger than that of any other group. In emerging countries, 80% of the collected waste is disposed of in open dumps or sub-standard landfill sites.[15]

Greenhouse Gas Emissions

The decomposition of post-consumer waste accounts for 5% of total global greenhouse gas (GHG) emissions. Organic waste decomposing in landfills is a major contributor, responsible for 12% of the global emissions of methane, a gas with a greenhouse effect 28 times greater than that of carbon dioxide (CO2).[i]

The rapid population growth and urbanization expected in low-income countries in the near future will lead to a huge increase in the volume of MSW generated. A large proportion of it will be organic waste, which will drive a significant increase in GHG emissions if landfilled or left to decompose. Cost-effective solutions exist, however, to capture and recover landfill gas to generate electricity and thermal energy. A 2013 report from the Methane Finance Study Group indicated that reductions of 1.6 billion tonnes of CO2eq at landfills would be possible between 2013 and 2020 if a $10 or lower incentive were added per tonne of CO2eq.[ii]

[i] Intergovernmental Panel on Climate Change (IPCC).
[ii] Methane Finance Study Group, Methane Finance Study Group Report, 2013.

Cities around the world have been implementing programmes to recover and valorize organic materials, such as those found in food waste and wastewater streams. However, the approaches to recovery and the volumes of recovered material vary greatly.

Some cities have achieved high rates of recovery of organic waste. Milan, Italy has covered large producers, such as restaurants, canteens and grocery stores since 1995, and instituted separate collection of organic solid waste from households in 2012. The collection programme now covers the city's entire population and recovers more than 130,000 tonnes of organic solid waste per year, more than any other city in the world with a population of over 1 million.[16] The collected material is used as input for anaerobic digestion and to generate biogas and compost. (For more about this initiative, see the "Milan" box.) In the United States, San Francisco and Seattle have implemented separate household collection of organic solid waste, with San Francisco collecting and recycling or composting 80% of the waste generated by its citizens.

Milan: Food Waste Recovery in a Densely Populated European City

In 2011, Milan had an overall separate collection rate of 35%, with food waste only collected from commercial sources, such as restaurants and hotels. Considering this level as unsatisfactory, the newly elected city government started a programme that would produce biogas and compost from residential food waste separated at source and sent to an anaerobic digestion and composting facility.

By January 2015, the total separate collection rate had risen to 53.5%, with food waste as the main contributor (projected at 95 kg/inhabitant). Milan is distinctive: it now covers 100% of the population, or 1.4 million people, which makes it the largest formal kerbside scheme in the world for collecting organics.

An information campaign was rolled out before starting the collection, and every household received a kitchen caddy along with a roll of 25 compostable bags made from bioplastic. Once the bags are full, they are placed in 120-litre bins (or in smaller buckets of up to 40 litres for detached and terraced houses, or small apartment buildings) and collected twice a week. The food waste is delivered to four transfer stations, from where it is transported on the same day to the anaerobic digestion and composting plant for producing biogas and compost.

Every tonne of diverted food waste represents a financial benefit: treating food waste costs about €70 per tonne, while the average disposal cost for residual waste is €100 per tonne. It also prevents food waste from decomposing in landfill sites and emitting GHGs, an important reduction in the environmental footprint.

In other cities, separate collection of organic waste is still in the early stages of development. New York City established an organics collection pilot programme in 2013, which now serves approximately 270,000 households. Two years after initiation, 15,850 tons of organic material had been collected, nearly 7% of the 2.2 million tons generated in the same period. This programme continues to scale up, with the goal of achieving zero waste to landfill by 2030.[17] Overall, however, the recovery rate for organic materials in the United States is low, with the rate for food waste as low as 4.8%.[18]

Many cities lack programmes for recovering organic waste. In the United Kingdom, for example, 40% of local authorities do not have a food waste collection scheme.[19] In Kumasi, Ghana, 80% of the nutrients in the 950,000 tonnes of food biomass that enters the city annually is lost because of the lack of collection infrastructure (see the Kumasi case study). Those nutrients end up on the streets and in drains, and concentrate in the surrounding soil, with a small percentage in landfill.[20]

Case Study: Kumasi (Ghana)[i]

Kumasi, a city of 1.2 million people, sources its food primarily from the surrounding rural area. In 2007, the estimated annual inflow of food into the city was 950,000 tons, equivalent to 80% of the city's requirement, with the remaining 20% provided by imports. The quantity of nitrogen in the inflowing food exceeded the total amount of nitrogen fertilizer imported annually into the country.

The lack of adequate recovery infrastructure has meant that the bulk of the organic material entering the city ends up on the streets, in drains or in landfills. A material flow analysis conducted in 2002 found that about 80% of the phosphorus and nitrogen entering the city was lost or leaked into the surrounding environment. About half of the nitrogen accumulated in ground and surface water, and about 15% of both nutrients were sent to landfill, with less than 5% ending up in treatment plants. The nutrient value of the uncollected solid and liquid waste would have been sufficient to pay for the city's entire solid waste management costs of $180,000 a month.

[i] Drechsel, P., Graefe, S. and Fink, M.

Advanced Solutions for Integrated Waste Management

SUEZ, the industrial services company, has developed a dedicated integrated solid waste management offer for emerging countries, demonstrating that simple and affordable solutions exist for managing urban organic waste.

These solutions use simple technical modules to convert waste into valuable materials and energy, capturing the full potential of this resource stream. Modules include the following: sorting and separating to recover high-value materials; diverting from landfill and transforming organic waste into new resources, such as fuel, compost and fertilizers; producing energy through the generation of biogas on the landfill site; and optimizing intelligent systems to increase energy performance and save empty landfill space.

These services are implemented locally and adapted to suit the local context. In Meknés, Morocco, for example, the rehabilitation and construction of sanitary landfill sites and a new composting plant also included establishing a cooperative to help integrate local waste-pickers into the solution.

This integrated approach provides an answer to local waste management needs, protects human health, cleans the urban environment, reduces atmospheric pollution and supports local economic development. Additionally, initial analyses estimate that implementing such solutions would help cut GHG emissions at a cost of less than $15 per ton of CO2eq avoided, depending on the initial situation.

High-Income and Emerging Economies

Food waste is a significant issue in both high-income and emerging economies. While the two groups make up relatively similar proportions of global food waste – 56% from high-income and 44% from emerging economies – the stages in the value chain where waste occurs vary significantly. More than half of the food waste in North America, Europe and Oceania occurs at the consumption stage, whereas most of the waste in South Asia, South-East Asia and Sub-Saharan Africa occurs at the production and storage stages (the two stages closest to the farm).[21] This contrast indicates the need for tailored approaches to recovering and valorizing organic waste in different regions of the world.

However, almost all urban areas, no matter where they are located, experience significant levels of food waste and loss. This is particularly true in emerging economies, which often lack the necessary infrastructure to deal with the problem.[22]

The Urban Opportunity

The capability of cities to recover organic waste varies greatly around the globe, and even within the same country, whether it is high or low income. Clearly, a significant opportunity exists to increase the recovery of organic material across the board. Well-designed and well-operated integrated waste collection and recovery schemes have been shown to recover upwards of 85% of the organic waste produced. However, average rates are actually far below this. In OECD countries, only 66 million tonnes of organic waste, or 37% of the roughly 180 million tonnes generated in 2013, was either composted or anaerobically digested.[23]

Although municipalities currently view organic waste management as a cost, it could be an attractive source of revenue. A 2013 study by McKinsey and the Ellen MacArthur Foundation highlighted from two perspectives the potential value that could be derived from processing food waste with anaerobic digestion: one, mitigating the problem of steeply rising landfill costs; and the other, receiving revenues from sales and subsidies for renewable energy. In the United Kingdom, an estimated operating profit of up to $172 per tonne could be achieved, including $26 from electricity, $18 from heat and $6 from fertilizer. The feed-in tariff was taken at $64, avoided land fill costs were $105, and an allowance of $45 was made for sorting and processing.

Cities are concentrators of organic material, with imbalances between inflows and outflows leading to aggregation at the urban level. While this makes cities the source of large amounts of waste and systemic leakage in the current economic model, these resource streams would be captured and valorized in the circular model. Ultimately, a city should function like an ecosystem, providing ecosystem services that are indistinguishable from the surrounding environment. Cities present a major opportunity to implement circular principles in the biocycle economy when combined with their characteristics, which include the scale of supply, the proximity between stakeholders and a tech-savvy workforce.

Water and Cities

People have lived in rural environments for most of history; in fact, in 1800, only 3% of the world's inhabitants were in cities. While this level had grown to 14% by 1900, only 12 cities at the time had populations of over 1 million. By 1950, the proportion had increased to 30%, and by 2008 the world reached an even split between rural and urban living, with more than 500 cities having over 1 million inhabitants. In 2050, it is estimated that over 70% of people will be living in cities, equivalent to 2.5 billion new urban dwellers.

Ever since cities were first founded, their prosperity has been closely linked to their water supply's reliability and quality. A rapidly urbanizing world means an increase in water consumption, as well as more demands on the resources and infrastructure required to provide safe and reliable water systems. Currently, one in four cities in the world suffers from water stress,[i] or the struggle to provide for its human and ecological needs. About half of China's 657 cities are categorized as water scarce or severely water scarce. In São Paulo, Brazil, the largest city in the western hemisphere, the water reservoirs were so low in 2015 that its residents faced daily 12-hour shut-offs. By 2040, global water demand could exceed water supply by an estimated 50%.[ii]

Cities have a huge water "footprint", as they move about 430 billion litres per day through pipes and aqueducts totalling over 17,000 miles. While cities occupy a total land surface of only 1%, their catchment area for providing water is about 41%. As an example, the watershed supplying New York City is 2,000 square miles, with some drops of water travelling over 100 miles through vast aqueducts before entering the city's water supply system. The water supplying Los Angeles, California travels 230 miles from source to city. Although cities' impact on water can have a huge effect on a wide surrounding area, it goes both ways. Pursuing better farming practices on just 0.2% of farmlands in urban watersheds could improve water quality for 600 million people. Ensuring safe and resilient water supplies in the future for cities is a great and complex challenge; no wonder many experts are calling it a looming crisis.[iii]

Nowhere are these challenges more evident than in India's cities. In the next two decades, the country's urban population is projected to grow from 400 million to 600 million. Urbanization, accompanied by an expanding middle class, will push up per-capita consumption. In fact, a 50% increase in urban population may increase the associated annual demand for water by 100%, from 740 billion cubic metres (m3) to 1.5 trillion m3.[iv] This represents both a challenge and an opportunity for the future. Currently, only 30% of household wastewater is treated; the rest discharges into open drains or the ground, eventually finding its way into aquifers and waterways, both sources of drinking water. A report by the Central Pollution Control Board in March 2015 estimated that Indian cities produce 62 billion litres of wastewater per day, whereas the total treatment capacity is only 23 billion litres.[v] Of this installed capacity, 70% is estimated to be non-functioning because, according to a government spokesman, the cost of energy to run the plants is prohibitively high. All of this puts a huge strain on the national economy, as well as on environmental and public health (one estimate puts this impact at $54 billion, or 6.4% of GDP).[vi]

The huge future demand from Indian cities, combined with the current non-functioning wastewater systems, suggest that new approaches to wastewater treatment is needed. As Ger Bergkamp, Executive Director of the International Water Association, emphasizes: "The wastewater treatment plant, as we know it today, is no longer fit for purpose. Major benefits can come from truly rethinking the entire urban water, carbon and energy systems. This approach would be a crucial part of establishing a circular economy in which water and material loops are closed."

[i] McDonald, R. et al.
[ii] ING.
[iii] Borrell, B.
[iv] Balasubramaniam, H.
[v] The Economic Times.
[vi] Alba, D.

Nutrient Recovery

The cycling of nutrients is critical for the growth of all plant and animal life on the planet. At its most basic level, the natural cycle sees nutrients such as nitrogen, phosphorus and potassium absorbed from the soil by plants, which are then consumed by animals (including humans). These nutrients are subsequently excreted and returned to the soil, where plants can take them in again.

This cycle, however, has been disrupted by human activity. Modern agricultural practices, such as excessive tillage and the use of heavy machinery, accelerate erosion and water runoff, carrying nutrients out of the soil and into water systems. As crops are harvested, nutrients and organic matter are removed; if they are not replaced, soil fertility decreases. Excessive use of pesticides and synthetic fertilizers, which may not contain all the necessary nutrients and organic matter, can also lead to increasing toxicity levels, reducing the soil's capacity to support growth.

As more and more nutrients are lost and soil quality decreases, so farmers increasingly turn to using synthetic fertilizers. Global demand for fertilizer was estimated at 185 million tonnes in 2014, and is forecast to grow 1.6% annually.[24] Producing synthetic fertilizers typically involves mining finite resources such as phosphate rock, requires significant energy and generates GHG emissions. Producing synthetic nitrogen fertilizers, for example, consumes 2% of the world's energy and, in 2007, generated 465 million tonnes of CO2 emissions.[25]

In addition to farming practices, megatrends such as globalization, an increasing population and urbanization all contribute to disrupting the nutrient cycle. The global food system and trade networks, for instance, can require extracted nutrients to be transported vast distances from their source. Increasing urbanization leads to nutrients being concentrated and discharged as food waste into solid waste streams, and into wastewater systems as sewage sludge. In Europe, the sludge contains approximately three times more phosphorus than is found in solid waste.

Rather than returning to the soil, the nutrients in these waste streams go largely unrecovered, ending up in landfills or polluting urban soils and water systems. For example, among the EU-27, 70% of the phosphorus in sewage sludge and biodegradable solid waste goes unrecovered.[26] In Bangkok, an estimated 90% of the 26,000 tons of nitrogen that enter the city each year is lost, primarily through the city's waterways.[27] Fertilizer runoff from the agricultural system, and concentration and discharge of nutrients in wastewater systems, lead to nutrients accumulating in rivers, lakes and oceans and eventually to eutrophication, algal blooms and hypoxic dead zones.

The crux of the issue is that nutrients are extracted from the biosphere as harvested food, become concentrated in cities, and then cause damage where they are discharged, rather than being beneficially looped back into the soil.

Circular Economy Vision

In a circular system, all nutrients would be returned to the biosphere in an appropriate manner. In the urban context, this means the nutrients are captured within the organic fraction of MSW and wastewater streams, and processed into a form suitable to be returned to the soil, such as organic fertilizer. The recovery of post-consumer nutrients, coupled with the more effective use of nutrients associated with regenerative agricultural practices, would reduce the need to bring in nutrients from non-renewable sources, such as synthetic fertilizers. This would all contribute to developing a regenerative closed-loop nutrient cycle.

Solutions and Potential Impact

Urban waste streams represent a significant opportunity to recover nutrients and return them to the soil. Solutions and technologies to do this already exist, and are being implemented in various locations and at different scales around the world.

Such solutions include composting, or the predominantly aerobic, biological decomposition of organic materials. In this process, organisms such as snails, worms, fungi and bacteria help to transform the material over time into humus, a critical component of healthy, fertile soil. Another solution is anaerobic digestion, in which micro-organisms break down biodegradable material in the absence of oxygen. It is effective in producing organic fertilizers rich in nutrients and organic matter, in addition to renewable energy.

Compost and digestate differ in their nutrient content and the availability of those nutrients for uptake by crops. The benefits of applying high-quality compost to soil have been widely documented; they include increasing the organic matter in soil, improving water retention and increasing biological activity. Comparatively less well characterized are the long-term effects of applying digestate, a nutrient-rich substance that remains after anaerobic digestion, on soil organic matter and structure. Generally, compost is viewed as having superior soil-improving qualities, while digestate is better suited as a biofertilizer.[28]

Several cities around the globe employ these processes to treat collected organic waste, with solutions ranging from backyard and community composting schemes to large-scale anaerobic digestion facilities. Examples include the city of Adelaide, Australia, which composts about 70% of its organic waste, and New York City's Compost Project, which provides educational materials to encourage household composting and has set up drop-off sites for community composting.

An additional approach is through extracting phosphorus and nitrogen from wastewater systems through solutions such as Veolia Water Organics Recycling, SUEZ's Phosphogreen technology and Ostara Nutrient Recovery Technology's Pearl Process (see Ostara case study). Recovering nutrients from wastewater not only reduces costs for wastewater treatment plants, which face increasingly stringent limits to prevent the harmful discharge of polluting nutrients into adjacent waterways, but also helps such plants to eliminate the build-up of struvite scale in pipes. This reduces operating costs and creates a revenue stream for the municipality through sales of high-value fertilizer.

Case Study: Ostara Nutrient Recovery Technologies

The Pearl technology developed by Ostara is a closed-loop nutrient recovery solution. It can recover 85% of the phosphorus and up to 15% of the nitrogen from municipal and industrial wastewater streams, and transform them into a high-value fertilizer.

According to Ostara, nutrients crystallize into highly pure fertilizer granules and grow in diameter after the addition of magnesium in a controlled pH setting. Once they reach the size required for standard fertilizer blends, they are harvested, dried and bagged – ready for immediate distribution and sale.

The fertilizer recovered by the Ostara process has a distinctive crystalline composition that releases nutrients when acids are given off by growing plant roots. This maximizes the efficiency of phosphorus uptake and therefore minimizes phosphorus leaching and run-off. The process helps to ensure that the plant absorbs the nutrition, thus contributing positively to the growing cycle as opposed to nutrients being lost in waterways.

Capital costs are recouped in 5-10 years through annual savings in chemicals, sludge disposal and maintenance, as well as revenue from Crystal Green fertilizer sales. In addition, the solution helps protect local waterways from nutrient pollution (through lower application and release rates, and lower water solubility) at a time when clean water, food security, fertilizer run-off and growing populations are issues for communities around the globe. The use of one tonne of Crystal Green eliminates approximately 10 tonnes of CO2eq emissions.

Estimating the potential impact of these solutions is difficult; however, several indicators point to the scale of the opportunity. Within the municipality of Amsterdam, for example, nutrient recovery has been estimated at a potential value of about €30 million per year. This would reduce the city's CO2 emissions by 300 kilotons (Ktons) and save 75 Ktons of material.[29]

In the EU-27, the phosphorus recovered from sewage sludge, meat, bonemeal and biodegradable solid waste amounts to almost 30% of the synthetic phosphorus fertilizer used (92% of which is imported).[30] Considering the low average levels of organic waste recovery across the continent (on average, 40% of organic waste collected in the EU goes into landfills[31]), an increase in organic waste collection could significantly augment the recovery of nutrients and further offset the use of synthetic fertilizers. In Australia, an additional 13 million tonnes of organic material per year could be diverted from the country's landfills. In fact, diverting just an additional 2 million tonnes would replace 10,000 tonnes of urea, 1,000 tonnes of phosphate and 5,000 tonnes of potassium sulphate, with the resulting yield improvements delivering another $30 million in farm revenue. Additionally, it would increase turnover in the organics recovery industry by up to $400 million, avoid approximately 2 million tonnes of CO2eq emissions and sequester approximately 1 million tonnes of CO2eq in soils.[32]

Nutrient Recovery from Wastewater

A person produces an average of 500 litres of urine and faeces every year. As the human body cannot absorb all the nutrients from consumed food, the excreted waste is full of valuable material. In a 2001 study, Swiss analysts estimated that if 100% of these nutrients could be captured in household sewage, nearly 30 million tonnes of nitrogen, 5 million tonnes of phosphorus and 12 million tonnes of potassium could be recovered globally, representing about a third of the annual total global demand for fertilizer.[i] The Commonwealth Scientific and Industrial Research Organisation in Australia found in a more recent study that "for a city of four million people, the total value of the carbon, ammonia, and phosphorus recovered would be USD 300 million per annum".[ii]

A closer look at one of these nutrient streams shows that phosphates are present in DNA, adenosine triphosphate and the lipids that form all cell membranes. Phosphate fertilizers are needed to replace the phosphate that plants remove from the soil. As the global population increases, demand is steadily rising, meaning more crops are cultivated and more meat is consumed (which has a higher "phosphorus footprint" than vegetables). In the past, the phosphorus cycle was closed; people and animals consumed food and excreted faeces, which were returned to the soil, nurturing it and helping to grow new crops. With shifting demographics, growing cities and "modern wastewater treatment", this cycle has been broken. Nutrients are not returned to the soil, but instead often end up in natural water bodies causing damage to aquatic ecosystems. While experts differ on the amount of natural phosphate reserves, most agree that they are dwindling (the US Geological Survey estimates that 80 years of phosphorus reserves remain).[iii] The price of phosphorus has been very volatile over the past several years; in 2008, the price increased by a factor of 10 in a matter of months.

A more holistic approach to phosphorus is required to close the loop between food, people and soils, and prevent its leakage into bodies of water. Recovering phosphorus from wastewater could be part of this solution.

[i] Smil, V.
[ii] Ellen MacArthur Foundation, Towards the Circular Economy, Vol. 2, p. 45.
[iii] MIT, Mission 2016: The Future of Strategic Natural Resources.

Urban organic waste streams are not the only potential sources for nutrient recovery. In Japan, for example, the amount of phosphorus in dephosphorization slag from the steelmaking industry is comparable to the country's total imports of phosphate ore. Technologies are being proposed to capture this source.[33]

In theory, the recovery of 100% of the nitrogen, phosphorus and potassium in global food, animal and human waste streams could contribute nearly 2.7 times the nutrients contained in current volumes of chemical fertilizer.[34]

Barriers to Overcome

Barrier Type	Description
Policy and regulation	– Nutrient recovery – Most cities are not mandated to recover nutrients from their organic waste streams. – Imports and exports – Although the market exists, members of the European Union find it difficult to import and export organic fertilizer and soil amendments, such as struvite.
Economic	– Lack of capital – This includes government funding, and hinders infrastructure development. – Unaccounted for and unpriced externalities – These are both positive and negative, and mean that organic fertilizers do not compete on a level playing field with inorganic fertilizers.
Market	– Competition on cost – Organic fertilizers need to compete on a cost basis with inorganic fertilizers. – Inability to assess comparative benefits/impacts of different treatment options on a level playing field – For example, while decentralized wastewater treatment could dramatically reduce power use and costs associated with sewer maintenance, it is unlikely to be economic enough at this small scale to recover nutrients. – In the United Kingdom, fiscal incentives have skewed choices (e.g. credits for renewable energy production have valued carbon above nutrients).
Technological	– Need to convert facilities – Existing chemical treatment facilities must be converted to biological processes.
Social	– Failure to recognize the full benefits of using compost and digestate – Farmers do not realize such benefits for their soils (such as increased carbon and organic matter, improved soil structure and water retention), compared to using manufactured inorganic fertilizers.

Biorefineries

Fossil feedstocks are included in many of the products and materials currently produced in petrochemical refineries, including oil, fuel, chemical feedstocks, plastics and synthetic materials. Significant opportunity exists, however, to use organic waste material to manufacture a range of these products and materials that are traditionally derived from fossil fuel. This is particularly of interest as fossil feedstocks dwindle and prices become increasingly volatile.

Biorefineries can employ a range of techniques, such as thermal treatment, biological processes and enzymatic conversions, to transform organic material into valuable chemicals and products. These products are broadly classified into three categories:

1. **High value, low volume**
   - Specialty chemicals (e.g. limonene, serum albumins)

2. **Medium value, medium volume**
   - Commodity chemicals (e.g. polyhydroxyalkanoates, polylactic acid, acetone, lignin derivatives)
   - Carbon fibre and cellulosic materials (e.g. crystalline cellulose, carbon fibres from lignin)
   - Biofuels (e.g. bioethanol, biodiesel, biogas)
   - Fertilizers (e.g. meat and bonemeal, struvite)

3. **Low value, high volume**
   - Compost
   - Digestate

Biorefineries have many available options for feedstock. A useful categorization distinguishes between first- and second-generation feedstocks. First-generation refers to feedstocks drawn from edible biomass, such as corn and sugar cane, while second-generation feedstocks are derived from residual non-food parts of crops, organic waste streams or other non-food sources, such as algae. Second-generation feedstocks have garnered significant interest (see DSM case study); they not only extract the maximum value from available biomass and turn waste into resources, but also reduce competition for agricultural land that can otherwise be used to grow food crops.

Case Study: DSM – The Cellulosic Ethanol Revolution

Cellulose is the world's most abundant organic compound and provides the cellular structure for trees, grass and, in fact, all plant life. Producing cellulosic ethanol from biomass has enormous potential; such biomass includes agricultural residues, such as corn cobs, leaves, stalks, straw, grasses and waste wood, and even municipal waste. Project LIBERTY, the first initiative of POET-DSM Advanced Biofuels, is a 50:50 joint venture between POET, a US-based ethanol producer, and Royal DSM, a global science-based company. The project offers substantive proof of the technological and commercial viability of advanced biofuel production using second-generation feedstocks. The Project LIBERTY plant began shipping cellulosic ethanol at the end of 2015. At full capacity, it will convert 770 tons of biomass per day to produce ethanol at a rate of 20 million gallons annually, and later ramp up yearly production to 25 million gallons.

To make cellulosic bioethanol, agricultural residue from corn needs to be pretreated with acid or heat. Enzymes are added to extract all sugars, proteins and lignin from the plant material. Finally, yeasts "eat" these sugars and turn them into bioethanol. While the theory is straightforward, the process is exceptionally difficult in practice. The sugar molecules contained in lignocellulose are well protected by tightly packed cellulose chains (part of a plant's natural defence system). Sophisticated biotechnology is required to break down these chains and get to the sugars.

DSM made a major scientific breakthrough in 2008 by identifying enzymes in its strain collection with the desired performance characteristics. Real progress was also made in developing an enzyme system particularly effective at breaking down lignocellulose into component sugars.

Biorefineries will start to produce increasingly complex chemicals and materials as the technology matures. Succinic acid and polylactic acid are already examples of this, as plant "waste" is increasingly seen as offering competitive alternatives to fossil resources. As a consequence, these facilities will become true biorefineries, producing a whole range of valuable products beyond advanced biofuels from feedstocks that were previously viewed, and treated, as waste.

Circular Economy Vision

Biorefineries could become an integral component of urban waste management infrastructure, receiving the organic fraction of MSW as well as wastewater streams, and converting it into valuable materials and products. A diverse set of solutions at multiple scales within the urban environment could be developed to fit local contexts; they could be tailored to suit local needs, the local collection infrastructure and the content of the incoming organic feedstock to determine which outputs to produce.

Solutions and Potential Impact

Small- and large-scale biorefineries, located in urban areas close to the source of input material, have both the opportunity and the technologies (see the Biopolus and Ecala case studies). Research conducted in the Netherlands estimated that the potential net value created from implementing a network of biorefinery hubs in Amsterdam could total €30 million per year. Further, such a system is estimated to reduce CO2 emissions by 100 Ktons and yield material savings of 25 Ktons.[35]

Case Study: Biopolus – Metabolic Hubs

Redesigning urban metabolism could support cities in investing directly in effective organic treatment solutions that close water, food and nutrient loops, and generate energy, all while bringing about social benefits. Biopolus is looking to create an interconnected network of water recycling associated with energy production and organic products growing in its metabolic hubs.

These aesthetic hubs are suited to all types of settlements, ranging from industrial parks to luxury residential communities and slums. Thanks to high modularity in size, layout and function, they can fit into any environment, as part of a new construction or as a retrofit. Modules provide functions suited to the local community's context, such as generating energy, treating water, recovering nutrients, and even providing bathroom blocks and laundry facilities. The Aero.Green aeroponics module, for instance, adopts a special lightweight and mobile method of urban farming, allowing the hub to produce healthy, nutritious food for a large population and where water is scare and space is limited.

Each individual hub can be set up to serve anywhere from 5,000 to 50,000 people. Using metabolic network reactor technology, a microecosystem with more than 2,000 species, including bacteria protozoa, invertebrates and plants, turns the hubs into a living factory. The modular hubs require up to 60% less land and save up to 35% in operational costs compared to traditional solutions.

Case Study: The Ecala Group – Integrated Utility Hub

Ecala, a restorative infrastructure design, development and advisory firm, employs a whole-systems approach to guide public, private and social sectors to circular and net positive success. Its Integrated Utility Hubs (IUH) incorporate industry-leading technologies for resource recovery, water purification, energy generation and food production within a single, closed-loop facility. The IUH creates no adverse smells, noise or pollution, and can be placed in locations ranging from dense, high-income urban areas to remote villages, delivering services directly to local communities. Additionally, modular and scalable hubs can be designed to fit within International Standard Organization shipping containers, allowing them to be deployed rapidly to assist with disaster relief in remote regions or communities.
The core functions and production capabilities of a city-scaled IUH are:

- **Waste:** Processes 600 tonnes of unsorted MSW per day, with an 80-95% recovery rate
- **Water:** Purifies 5 million gallons of wastewater per day to potable levels, without using chemicals
- **Energy:** Generates emissions-free baseload electricity for 20,000 households, or pure hydrogen for 14,000 vehicles, from a combined heat, hydrogen and power system
- **Food:** Produces 1 million pounds of fresh fish and 4 million heads of lettuce per year, using 98% less space and 95% less water than conventional farming
- **Public asset:** Incorporates public amenities, including food markets, cafes, offices, laboratories and exhibition spaces

Billund Biorefinery

The Billund biorefinery, an award-winning project in Billund, Denmark, combines the strongest environmental technologies in water treatment and biogas in one significant, full-scale demonstration project. Using XELYS, Veolia's proprietary thermal hydrolysis and anaerobic digestion technology, the plant simultaneously treats Billund's wastewater from its 70,000 residents, as well as 4,200 metric tons of organic waste from agriculture, industry and local households.

The biogas generated is transformed into electricity and heat, and the nutrients are utilized in a very effective and odour-free organic fertilizer. The plant is able to produce up to 60% more biogas; it changes the balance between energy consumption and own production of energy, so that more energy is produced than required for treatment. Furthermore, the process opens up possibilities of using interesting by-products, such as phosphorus (fertilizer) and biodegradable bioplastics.

Benefits:
- Producing biogas from the biowaste and treatment sludge that provides heat and electricity for the site
- Producing organic fertilizer for agriculture, and bioplastics for industry
- Discharging treated water into the neighbouring stream
- Creating a city-country-industry loop
- Reducing the environmental footprint

Co-locating these biorefineries with existing facilities, such as wastewater treatment plants, could result in significant benefits from the synergies and cost-savings of collection, preprocessing and refining. Research has suggested that such co-locating could result in new capital savings of 20-80%, depending on the level of synergy.[36]

Numerous studies have tried to quantify the potential value of using biorefining processes, usually focusing on specific geographies or product categories. For instance, the World Economic Forum estimates that potential global revenues from the biomass value chain (the combination of produced agricultural inputs, biomass trading and biorefinery outputs) could be as high as $295 billion by 2020.[37] The United States is capable of producing 90 billion gallons of biofuels to replace oil, meaning that, with improvements in vehicle mileage, the country could run solely on biofuel by 2050. The limiting factor is not the supply of biomass, but rather the commitment to oil-focused infrastructure, low oil prices and lack of political decision-making.[38]

The market for lignin-derived chemicals (benzene, toluene, carbon fibre), which are in products such as motor fuel, activated carbon and plastic materials, is estimated to be over $130 billion and projected to reach $208 billion by 2020.[39] Moreover, the Finnish government forecasts its national bioeconomy to grow 4% annually to 2025, increasing economic output from €60 billion to €100 billion, and adding 100,000 jobs. The greatest opportunities for growth are expected to be in creating new products and materials, with organic waste streams playing a significant role as raw materials.[40]

The European Commission estimates that the European bioeconomy is worth approximately €2 trillion in turnover per year, and accounts for more than 22 million jobs, although this figure includes materials other than waste. (It encompasses the production of renewable biological resources and the conversion of these resources and waste streams into value-added products, such as food, feed, bio-based products and bioenergy.[41])

None of these studies gives a global figure for the size of the existing opportunity. They do indicate, however, that significant value creation is possible provided the barriers to scaling up the implementation of biorefining technology can be overcome.

Resource Recovery from Wastewater

"Wastewater is the largest untapped waste category – as big as all solid waste categories taken together. It is a natural starting point for the circular revolution."
– Martin Stuchtey, "Rethinking the Water Cycle", McKinsey & Company

If a value could be attached to the resources in sewage flows, the idea of wastewater treatment would shift from an expensive cost centre to a profit-generating "resource factory", one that creates a variety of useful end products. In the circular economy, the flow of biological nutrients can be seen as a series of cascading, value-extracting stages. In a similar way, wastewater could be viewed as a rich soup of energy, carbon, nitrogen, phosphorus and other ingredients that yield different products at different stages. The final and often most valuable product would be clean water, which can be reused or safely returned to the biosphere.

A material analysis conducted by the Green Ribbon commission of Amsterdam's annual wastewater production (the city's population is about 800,000) demonstrates the potential value of urban wastewater:[i]

- Water – 72 million cubic metres (2 billion cubic metres in the Netherlands)
- Organic matter – 40,041 tons
- Phosphorus – 577 tons
- Nitrogen – 4,140 tons
- Heavy metals – 28.8 tons
- Pharmaceuticals – 3.1 tons

Extracting resources, such as energy, fertilizers and compost, is well established (see the "Nutrient Recovery from Wastewater" and "Energy Recovery from Wastewater" boxes) and already widely practised around the world. A number of issues, however, are holding back more widespread adoption for other products:

- Maturity of technology: The recovery of cellulose and algae products, for example, is still at the demonstrator stage.
- Competition on price, quality and scale with incumbent producers: For instance, succinic acid, a flexible chemical precursor for many commercial products, already has well-established industries with economic production methods.
- Regulatory and environmental context: For example, variations exist in the allowable concentration of nitrogen in effluent linked to the nature of local receiving water. Removing nitrogen is expensive, requiring energy and carbon, which in turn influences a plant's economics and its ability to generate revenue.

To illustrate this last point, too much nitrogen in effluent can create dead zones, as algal blooms form and lead to hypoxic conditions which suffocate aquatic life. This is the context for many treatment plants in New York City that discharge into the ecologically sensitive Long Island Sound. More stringent effluent quality requirements have led to billions of dollars of investment to upgrade the denitrification capacity of the adjacent treatment plants.

In comparison, San Francisco's East Bay Municipal Utility District discharges effluent into the Pacific Ocean with much less stringent nitrogen permitting. Add to this the unit cost of electricity in California, which is among the highest in the country, and the combination of factors led the utility to modify its plant to process both food waste and sewage. Extra carbon-rich biomass allows it to increase production of biogas, which it converts to electricity to sell to the local grid. The nitrogen and phosphorus from the process, which is normally a costly operation of recovery and elimination, is then discharged into the ocean.

While this is not a "circular" model to be emulated, it does illustrate pragmatic issues in a local context that can determine how wastewater treatment plants are designed and operated. The Table summarizes the products that potentially can be recovered from sewage flows, along with the associated technology's maturity level and any related case studies.

Fossil fuels currently provide more than 60% of the energy consumed by OECD countries, while only 1% of the energy consumed is generated by waste. Approximately 10% (50

Table: Potential Products from Wastewater Treatment Plants

Group	Products	Uses	Technology	Case Study
Water	Potable and non-potable water	Industrial, cooling water, landscaping, agriculture, aquaculture	High	NEWater (Singapore) Gorengeab plant, Windhoek (Namibia)
Energy	Biogas	Heat or electricity generation	High	Odense plant (Denmark) Thames Water (UK) (see the “Energy Recovery from Wastewater” box)
Treated sludge	Biosolids, biogrout, biochar	Soil conditioning, land reclamation, building materials, nutrients	High	Widespread use
Nitrogen and phosphorus	Phosphates, detergents, phosphoric acid	Fertilizers	High	Ostara – Crystal Green (see the “Ostara” case study)
Cellulose	Recycled cellulose (Recyllose™)	Plastics, insulation, cardboard, construction	Medium to high (number of installations around the world)	Applied CleanTech[a)]
Algae	Biodiesel, alginates	Fuels, animal feed, paper industry (alginates), pharmaceuticals, cosmetics	Low to medium (rotating algae bioreactors – prototypes in the US)	WesTech Engineering[b)]
Commercial chemicals	Succinic acid, ethyl acetate, methyl acetate, butyric acid	Platform chemical for many sectors	Low	Integrated BioChem[c)]
Data	Public health data sets	Predicting disease out-breaks, neighbourhood health	Theoretical	MIT Underworlds pro-ject[d)]

[a)] Applied CleanTech, Leading the Sewage Mining Revolution; [b)] Griffiths, F. [c)] Integrated BioChem, "Products" [website]; d) Massachusetts Institute of Technology, "Underworlds" [website].

[i] Struker, A.

Barriers to Overcome

Barrier Type	Description
Policy and regulation	– Legislative frameworks – Across all OECD countries, wastes are defined and regulated to ensure they do not harm the environment or human health. While these principles serve their intended purpose, they can act as barriers to using waste as a resource. – Stringent controls: They can be placed on owners, transporters and processors of organic waste, with associated administrative costs that are not applied to non-waste primary materials. – Restrictions placed on moving and using wastes can impede their integration into established non-waste processes.
Economic	– Relative cost of fossil fuels – Prices and costs have an impact. Bio-based products generally have to compete on price with products derived from primary petroleum-based materials, and are thus affected by the price of oil even when their cost structure is not affected by oil. – Fossil fuel subsidies distort the cost competitiveness of secondary materials-based products (not a level playing field). – Lack of access to funding – This is critical for financing pilot and full-scale commercial plants and infrastructure. – Venture interest has been decreasing as funds come to understand the large capital requirement; and, uncertainty surrounds a biorefinery's profitability, as governments only provide short-term incentives where the horizon for success is the long term.
Market	– Integrating bio-based products into existing value chains – Bio-based products that directly replace molecules in existing supply chains (e.g. succinic acid) must compete with incumbent processes for production. – Novel bio-based products cannot be integrated easily into existing supply chains. For example, bioethanol can only be mixed into conventional fuel up to a volume share of about 15%. Bio-based polymers are difficult to integrate into existing polymer value chains, as they may have different properties. – Specific demand for bio-based products is not developed, as externalities (negative and positive) of bio-based and fossil-based products are not integrated into the economics and the market.
Technological	– Infrastructure development – The use of new capital for these needs does not always dovetail with collection, processing and manufacturing capabilities to create integrated facilities. – Inconsistent delivery of high-quality collected material is particularly problematic considering the high volume of the material.

Bioenergy

Fossil fuels currently provide more than 60% of the energy consumed by OECD countries, while only 1% of the energy consumed is generated by waste.[42] Approximately 10% (50 exajoules) of total global primary energy exajoules) of total global primary energy supply is provided by bioenergy. Most of that energy is consumed in emerging countries for cooking and heating, using highly inefficient methods such as open fires or simple cook stoves, which have a considerable negative impact on human health (smoke pollution) and the environment (deforestation).[43] A total of 370 terawatt hours (TWh) of bioenergy-derived electricity was produced globally in 2012, which corresponds to only 1.5% of the electricity generated.[44]

Not only are fossil fuels a finite resource, but the significant negative impacts of generating energy from them are also well understood and documented. For instance, coal represents roughly 40% of global energy production[45] and, in 2014, was responsible for 46% of global CO2 emissions.[46]

One of the core characteristics of a circular economy is its being powered by renewable energy, be that solar, wind, hydroelectric or bioenergy. The shift away from fossil fuel-derived energy towards renewables is already well under way. In 2015, renewables accounted for more than half the total annual additions to global power capacity, surpassing coal in cumulative installed capacity.[47]

Circular Economy Vision

In a circular economic system, the renewable energy produced as a byproduct of treating recovered urban organic waste would contribute to the energy used to power the city. In combination with other technologies, such as solar and wind power generation, a circular city would run entirely on renewable energy.

Solutions and Potential Impact

Anaerobic digestion can be applied to a wide range of organic material (e.g. food waste), generating biogas and digestate as outputs. Other than offsetting fossil-based energy production, an additional benefit of producing energy through anaerobic digestion is creating digestate, which returns nutrients to the soil, offsetting the use of inorganic fertilizers. Research has also suggested that aerobically post-composting digestate improves its capacity to increase soil's biological activity, helping to rebuild soil quality.[48]

Numerous examples around the world demonstrate how anaerobic digestion is used to treat organic waste and generate electricity. For instance, the United Kingdom has over 200 anaerobic digestion plants, 83 of which use municipal or commercial feedstocks. An additional 400 plants have applied for or been granted planning permission, indicating the strength of the pipeline that can be delivered with the right support.

As of 2016, the United Kingdom has the anaerobic digestion capacity to generate 617 megawatts of electricity equivalent, enough to power 800,000 homes, and to produce 9 TWh of biogas, which is only 25% of the 35 TWh that could be generated if all suitable feedstocks were used with existing technology. Looking ahead to 2025-2030, the Anaerobic Digestion and Bioresources Association estimates that the generation capacity in the United Kingdom, with new feedstocks and process improvements, could be about 78 TWh.[49] Anaerobic digesters will treat approximately 2.1 million tonnes of food waste and 21 million tonnes of sewage sludge in the country in the 12 months from July 2016.[50]

SUEZ: Ametyst

SUEZ's Ametyst plant in Montpelier, France is the largest anaerobic digestion facility in the country, able to treat 173,000 tonnes of municipal solid waste per year, 56,000 tonnes of which is anaerobically digested.

The plant generates 19 gigawatts (GWh) of electricity and 7 GWh of heat, which is used for 1,500 households in the local neighbourhood of Griselles, as well as the clinical centre of Saint-Roch. In addition, 25,800 tonnes of compost are produced, and is applied to public green spaces and local agricultural fields.

Veolia: Artois

At the heart of an agricultural region in northern France, Veolia constructed the Artois anaerobic digestion site in 2012. This unit can reuse all types of organic waste – from agriculture (agricultural biomass, chicory roots), the food industry (biological muds, flotation fats, manufacturing off cuts, meat waste, catering fats, among others), authorities (grass, canteen waste) and supermarkets (unsellable packaged products). The site is equipped with a complete loop of solutions, from deconditioning to re-use. Packaging, such as cardboard and plastic, is separated from organic material before being sorted and directed to the appropriate recycling units.

The annual treatment of 25,000 tons of organic waste generates 3.5 million cubic metres of biogas each year and 8 GWh of electricity, or the amount consumed by 2,700 households. This energy is sold on and injected into the power grid, thus avoiding 2,000 equivalent tons of CO2 emissions each year.

Generating bioenergy brings with it the opportunity for decentralized, off-grid energy production at a variety of scales (see "Sainsbury's" box). Emerging markets that have inadequate central energy infrastructure view this as a particularly appealing prospect. Demonstrations of bioenergy generation can be found in rural areas; for example, SNV's Vietnam Biogas Programme constructed over 158,000 domestic digesters, providing energy for about 790,000 rural dwellers.[51]

Sainsbury's: Off-Grid Energy Production

Sainsbury's superstore in Cannock, United Kingdom, is run entirely on power produced from food waste generated by the store. At the end of each day, any unsold food from all Sainsbury's stores across the United Kingdom that is suitable for consumption is given to charities. Some is also turned into animal feed, but any surplus after that is sent to the nearest Biffa anaerobic digestion facility.

In the case of the Cannock store, the nearest facility is a mere 1.5 km away. Taking advantage of this proximity, a cable was installed linking the store directly to the anaerobic digestion plant, providing a direct supply of renewable energy produced from the store's own waste and ending its reliance on the grid for day-to-day power supplies.

Although the project involved an investment of about £280,000, the retailer estimates annual savings of roughly £140,000 thanks to reduced energy costs.

Capturing landfill gas in sanitary landfills is another solution for energy generation that could be applied when anaerobic digestion is not a viable alternative. This could include cities that have already committed to creating landfills or simply do not have the capital to invest in more complex organic waste processing facilities.

Veolia: Landfill Gas to Energy

In the commune of Plessis-Gassot near Paris, Veolia operates the Electr'od site, a successful example of transforming landfill gas to energy that produces the most renewable energy from biogas in France. The plant, designed by Veolia in partnership with Dalkia and Clark Energy, generates 130 GWh of electricity per year, equal to the consumption of 41,200 households (excluding heating) and corresponding to the electricity produced by 40 wind turbines annually. The electricity is sold to the French grid operator and used by households and businesses in the country.

In addition, Electr'od operates as a cogeneration plant, simultaneously producing 30 GWh of thermal energy yearly, or the energy consumed by 2,850 households. This thermal energy supplies a new district heating and domestic hot water network, marking the first time a French town has been heated using recovered biogas. The cost of heating for those Plessis-Gassot residents connected to the network that is supplied by Electr'od will be 92% lower versus the cost of heating by electricity, and 91% lower compared to heating by oil.

Energy Recovery from Wastewater

Treatment of wastewater follows the same basic steps: removal of solid waste, biological digestion, disinfection and discharge. The process requires significant energy, estimated to be 21 billion kilowatts (kWh) per year in the United States (at a cost of more than $1.3 billion) and equivalent to 0.5% of overall demand.[i] About 70% is used in the bioreactor stage to produce air and oxygen.

The theoretical embedded energy in wastewater exceeds the energy required to treat it by a factor of 14. Although much of this potential is difficult to recover, some treatment plants have proved that they can be net energy generators. One US study found that wastewater treatment plants, taken collectively, could meet 10% of the nation's demand for electricity.[ii]

New York City produces 1.4 billion gallons of wastewater each day, which must be treated before being discharged back into local bodies of water. The energy required for treatment it is estimated at 500-2,500 kWh per million gallons, which equals a daily energy bill of between $50,000 and $250,000.[iii] At such a significant cost, it requires a reliable power system. This helps explain the lack of success of this approach to treating wastewater in places like Africa and India (see "Water and Cities" box). However, an analysis of the chemical and heat energy in wastewater reveals that the water contains up to 14 times more embedded energy than that required for treating it. Approximately 80% of this energy is low-grade heat that is difficult to recover. However, if the remaining 20% were converted to biogas and then to electricity at a conversion efficiency of 40%, it would still be theoretically possible to achieve a power-positive treatment plant.[iv]

At an individual plant level, the technological front runner in turning theory into practice is in Odense, Denmark. Covering a population of 350,000, the Ejby Mølle treatment plant has achieved 110% self-sufficiency in electricity, meaning the plant produces more electricity than it consumes.[v] Opportunities to optimize this performance have been identified that could lead to even better results.

At the utility scale, Thames Water in the United Kingdom saved about £15 million on its 2013 power bills by generating 14% of its energy demand from sewage sludge.[vi] For the future, the utility is investing in new thermal hydrolysis equipment that conditions the sludge in a pressure cooker at 160° Celsius, breaking bonds and allowing more biogas to be extracted per tonne of sludge. By using anaerobic digestion along with solar and wind, Thames Water aims to satisfy 20% of its demand through renewable sources. As well as reducing energy bills, the more efficient conversion means less biosolids at the end of the treatment process. Moreover, it reduces the transport costs required to return the fertilizer-rich organic material back to farmland by £2 million.

[i] Central Intelligence Agency.

[ii] Scott, L.

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This selection of examples in treating wastewater demonstrates current approaches to using organic matter for generating energy. At a macro level, the European Commission has estimated that around 2% of the EU's overall renewable energy target could be met if all organic waste was turned into energy.[52]

Barriers to Overcome

Barrier Type	Description
Policy and regulation	– Policy uncertainty – Investors consider the risks of policy variability when thinking about investing in anaerobic digestion projects.
Market	– Lack of recognition of anaerobic digestion's true value – Not simply a source of energy, it has benefits that include returning nutrients and carbon to the soil and offsetting organic fertilizers. – Unaccounted for and unpriced externalities – These are both positive and negative, and mean that bioenergy does not always compete on a level playing field with fossil-derived energy.
Technological	– Investment in research and innovation – Advances in microbiology could increase the speed of digestion, meaning more feedstock could be treated and more energy created with similar assets. – However, anaerobic digestion operators are often at the limit of grid capacities. – Improvements in technology need to be matched with policy-making. – Project costs and financial viability – Improved separation and quality of incoming material would reduce operating costs and enhance the chances of projects succeeding financially. This could mean better source separation and collection of MSW.

Conclusion

Vast potential exists in shifting towards a circular economy in the biocycle, ranging from scaling up regenerative farming practices to producing algae for making bio-based materials. This report has focused specifically on opportunities for valorizing post-use urban nutrients and biomass by applying currently available technologies.

- Cities are expected to produce 2.2 billion tonnes of solid waste globally per year by 2025, almost double the 2012 levels. About 1 billion tonnes of this will be organic waste, based on current non-organic/organic ratios.

- The decomposition of post-consumer waste creates 5% of total global greenhouse emissions. A major contributor to this is organic waste decomposing in landfills, which generates 12% of global methane emissions. (Methane gas has a greenhouse effect 28 times greater than that of CO_2.)

- Growing populations and increasing urbanization could lead to a significant rise in organic waste generation (and its associated negative impacts). This is particularly acute in emerging economies, which are expected to generate 70% of global waste in 2025. In these markets, organics, the primary generators of methane, are estimated to make up 60% of the waste; and, 80% of collected waste is currently disposed of in open dumps or sub-standard landfill sites.

- Significant opportunities exist to valorize post-use urban organic waste, including the development of high-value products and materials in biorefineries, the creation of energy from biological sources and the capture of nutrients to be returned to soils. The capabilities already available to perform these tasks now need to be scaled up to fully realize the potential.

- While some cities have shown it is possible to collect up to 85% of organic waste, average collection rates are low around the globe. This highlights the big opportunity to increase collection rates and valorize recovered material.

- The decision of whether to collect organics separately has important implications – for integrating them in residual waste collection systems, for the quality of the collected waste and, therefore, for the opportunities to recover value from organic material through additional processes, such as biorefining. Data collected during the development of the European end-of-waste proposals for compost and digestate indicated that only separately collected organic wastes could be used as feedstocks to manufacture quality products; contamination levels and poor quality of mixed-waste-derived outputs were too high for use as an unrestricted product.[53] However, technological evolutions have increased the quality of mixed-waste-derived outputs, which remain as options when source-separate collection cannot be implemented.

Cities around the globe are beginning to recognize the value embedded in organic material flows, and many have put systems into effect and continue to implement them to capture that value. Implementation, however, is sporadic; approaches vary significantly; and levels of success are wide ranging. A systemic shift in how to deal with urban organic waste is required to realize the full value.

About the Ellen MacArthur Foundation

The Ellen MacArthur Foundation was established in 2010 with the aim of accelerating the transition to the circular economy. Since its creation the charity has emerged as a global thought leader, establishing the circular economy on the agenda of decision-makers across business, government and academia. The charity's work focuses on four interlinking areas:

Education

Inspiring learners to re-think the future through the circular economy framework
We're creating a global teaching and learning platform built around the circular economy framework, working in both formal and informal education. With an emphasis on online learning, the Foundation provides cutting edge insights and content to support circular economy education and the systems thinking required to accelerate a transition.

Our formal education work includes comprehensive Higher Education programmes with partners in Europe, the US, India, China and South America, international curriculum development with schools and colleges, and corporate capacity building programmes. In the informal education arena our work includes the Disruptive Innovation Festival, a global online and face-to-face opportunity to explore the changing economy and how best to respond to it.

Business and Government

Catalysing circular innovation and creating the conditions for it to flourish
Since its launch, we've emphasized the real-world relevance of our activities and understand that business innovation sits at the heart of any transition to the circular economy. The Foundation works with its Global Partners (Cisco, Google, H&M, Intesa Sanpaolo, NIKE Inc., Philips, Renault, and Unilever) to develop circular business initiatives and to address challenges to implementing them.

In 2013, with the support of our Global Partners, we created the first dedicated circular economy innovation programme, the Circular Economy 100. Programme members comprise industry leading corporations, emerging innovators (SMEs), affiliate networks, government authorities, regions and cities. The CE100 provides a unique forum for building circular capabilities, addressing common barriers to progress, understanding the necessary enabling conditions, and piloting circular practices in a collaborative environment.

Insight and Analysis

Providing robust evidence about the benefits of the transition
We work to quantify the economic potential of the circular model and develop approaches for capturing this value. Our insight and analysis feeds into a growing body of economic reports highlighting the rationale for an accelerated transition towards the circular economy, and exploring the potential benefits across different stakeholders and sectors.

The Foundation believes the circular economy is an evolving framework, and continues to widen its understanding by working with international experts including key thinkers and leading academics.

Communications

Engaging a global audience around the circular economy
The Foundation communicates cutting edge ideas and insight through its circular economy research, reports, case studies and books disseminated through our publications arm. We utilise new and relevant digital media to reach audiences who can accelerate the transition, globally.
In addition, we aggregate, curate, and make knowledge accessible through Circulate, an online location dedicated to providing up to date news and unique insight on the circular economy and related subjects.

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