LUC 7
Envirothon

Waste to Resouces

Resource Materials:

- Waste to Resources Study Guide

Contents

Resources in Red are not included in LUC7 competition

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Illinois Extension

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- Food Waste: Food: University of Illinois Extension
- Cleaning Up After a Disaster (illinois.edu)
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- Composting with Worms: University of Illinois Extension
- Anaerobic Digestion and Biogas Production Feasibility Study (uidaho.edu)
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02. Reuse, Recycling, and Waste Diversion

Current Environmental Issue Study Resources

Key Topic 2: Reuse, Recycling, and Waste Diversion

1. Explain how the practices of reusing or recycling products conserves natural resources.
2. Describe how recycled materials can be repurposed and further diverted from landfills.
3. Explain how waste can be repurposed.

Study Resources

The U.S. Recycling System - *US EPA 2019*

What it Means to Go Green: Reduce, Reuse, Repurpose, and Recycle -*Rebecca Mills, Utah State University Cooperative Extension, 2012*

Zero Plastic Waste- *Government of Canada, 2021*

Stockholm Biochar Project - *Nordregio, 2018*

Sustainable Materials Management: Non-Hazardous Materials and Waste Management Hierarchy - *US EPA 2017*

Safe Hazardous Waste Recycling - *US EPA, 2000*

The U.S. Recycling System

US EPA, 2020

America Recycles Pledge

Organizations, are you interested in working with EPA and others on recycling?

Check out our America Recycles Pledge page for more information and to sign the Pledge.

In the United States, recycling is the process of collecting and processing materials (that would otherwise be thrown away as trash) and remanufacturing them into new products.

U.S. Recycling System Overview

Learn More

- About America Recycles Day
- About Recycling Basics and Benefits
- About the Framework for Advancing the U.S. Recycling System
- About the Recycling Economic Information (REI) Report

While the recycling process often differs by commodity and locality, there are essentially three main steps: collection, processing and remanufacturing into a new product.

1. **Collection:** Recyclable materials are generated by a consumer or business and then collected by a private hauler or government entity.

2. **Processing:** The materials are transported by the collector to a processing facility, such as a materials recovery facility or paper processor. At the processing facility, the recyclables are sorted, cleaned of contaminants and prepared for transport to a milling facility or directly to a manufacturing facility. Some commodities may require additional processing for additional sorting and decontamination. For example, glass and plastic are often sent to glass beneficiation plants and plastics reclaimers, respectively, where they are processed into mill-ready forms.

3. **Remanufacturing:** After all necessary processing has been completed, recyclables are made into new products at a recycling plant or other facility, such as a paper mill or bottle manufacturing facility.

Benefits of Recycling

Recycling Saves Resources and Creates Jobs

Recycling is an important economic driver, as it helps create jobs and tax revenues. The [Recycling Economic Information (REI) Report]() found that, in a single year, recycling and reuse activities in the United States accounted for 757,000 jobs, $36.6 billion in wages and $6.7 billion in tax revenues. This equates to 1.57 jobs, $76,000 in wages and $14,101 in tax revenues for every 1,000 tons of material recycled. Environmental, economic and community benefits can be attained from recycling.

For the environment, recycling:

- Reduces the amount of waste sent to landfills and incinerators;
- Conserves natural resources such as timber, water and minerals; and
- Prevents pollution by reducing the need to collect new raw materials.

For the economy, recycling:

- Increases economic security by tapping a domestic source of materials; and
- Saves energy.

For communities, recycling:

- Supports American manufacturing and conserves valuable resources; and
- Helps create jobs in the recycling and manufacturing industries in the United States.

Current Challenges Facing the System

While the benefits of recycling are clear, growing and strengthening the U.S. recycling system to create more jobs and enhance environmental and community benefits will require multi-stakeholder collaboration to address the challenges currently facing the system. Current challenges include:

- Most Americans want to recycle, as they believe recycling provides an opportunity for them to be responsible caretakers of the Earth. However, it can be difficult for consumers to understand what materials can be recycled, how materials can be recycled, and where to recycle different materials. This confusion often leads to placing recyclables in the trash or throwing trash in the recycling bin or cart.

- America's recycling infrastructure has not kept pace with today's waste stream. Communication between the manufacturers of new materials and products and the recycling industry needs to be enhanced to prepare for and optimally manage the recycling of new materials.

- Domestic markets for recycled materials need to be strengthened in the United States. Historically, some of the recycled materials generated in the United States have been exported internationally. However, changing international policies have limited the export of materials. There is also a need to better integrate recycled materials and end-of-life management into product and packaging designs. Improving communication among the different sectors of the recycling system is needed to strengthen the development of existing materials markets and to develop new innovative markets.

- Stakeholders across the recycling system agree that more consistent measurement methodologies are needed for measuring recycling system performance. These more standardized metrics can then be used to create effective goals and track progress.

Actions Taken to Address the Challenges

Framework for Advancing the U.S. Recycling System

EPA and its stakeholders have been working together to move the America Recycles Pledge from a commitment to a collection action. EPA developed materials to summarize the workgroups' efforts through June 2019.

EPA and its stakeholders have taken the below actions since November 2018 to address the challenges facing the U.S. recycling system.

Stakeholder Dialogues

In 2018, EPA conducted a series of roundtable conversations with key stakeholders involved in the recycling system. The roundtables were a chance to hear different perspectives on the challenges and opportunities within the system. The conversations led to the identification of four key action areas, and stakeholders formed workgroups to further explore and develop actions around the areas. Within those areas, the stakeholders expressed ideas for future actions that federal, state and local governments; industry associations; recyclers; waste haulers; material users; and non-governmental organizations could take to improve the U.S. recycling system. The action areas are:

- Promote Education and Outreach;
- Enhance Materials Management Infrastructure;
- Strengthen Secondary Material Markets; and
- Enhance Measurement.

America Recycles Day Summit

On November 15, 2018, EPA Administrator Andrew Wheeler hosted the America Recycles Day Summit, which brought together stakeholders from across the U.S. recycling system to join EPA in signing the America Recycles Pledge. All 45 signing organizations, including EPA, pledged to work together to identify specific actions to take in addressing the challenges and opportunities facing the U.S. recycling system. Through the pledge, organizations committed to leveraging their collective expertise, strengths and resources to address these challenges and opportunities. Participants included representatives from federal, local, state and tribal governments; the recycling industry; and manufacturers and brands.

- For more information on actions taken after the Summit, view the Framework for Advancing the U.S. Recycling System.
- View pictures and a highlight video of the event.

America Recycles Pledge

We invite U.S.-based organizations to sign the America Recycles Pledge. Visit our page to sign the pledge and join others that have signed it to work toward a more resilient materials economy.

Families and Communities
Utah State University COOPERATIVE EXTENSION
extension.usu.edu
June 2012 Sustainability/Recycle/2012-01pr

What It Means to Go Green: Reduce, Reuse, Repurpose, and Recycle

Rebecca Mills, M. Ag.
Extension Assistant Professor
Family & Consumer Sciences/4-H Youth Development

People and businesses around the world are concerned about the environment and the availability of natural resources for future generations. This concern is evident in the development and marketing of products like energy efficient appliances, vehicles powered by alternative fuel sources, and even biodegradable potato chip bags. What does it all mean and why is it something to learn about or do? This fact sheet defines some basic terms related to resource use and shares ideas of how simple choices can have a positive impact on the well-being of citizens, businesses, and the environment.

Reduce

Simply put, reduce means "less" as in "use less" or "make less of." In environmental or "natural" terms it could mean something as simple as turning off the faucet while brushing teeth, thus REDUCING water use. Other ways to REDUCE could be:

- Carpool/walk/bike (reduce fossil fuel use, emissions).
- Turn off/unplug electrical appliances when not in use (reduce electricity use = $$ savings).
- Compost green waste like kitchen scraps or lawn trimmings (reduce garbage in landfill, create a usable product for later).
- Switch to energy efficient light bulbs and appliances (save on energy costs).
- Make double-sided copies (reduce paper use).
- Go electronic—emails, document sharing, online bills/bill pay (reduce paper use).
- Catch and store rainwater for outdoor watering (check first with local ordinances).
- Buy in bulk or purchase products with minimal packaging (reduce waste).
- Have household names/addresses removed from junk mail lists and credit card offers (reduce paper use; for more information visit www.dmachoice.org or www.optoutprescreen.com).

The Environmental Protection Agency (EPA) reports that paper products amount to 28.2% of all municipal solid waste generated in the United States which is the second largest category of all solid waste types reported. The largest category at 29.4%, titled "Other Wastes," includes food scraps, yard trimmings and miscellaneous inorganic wastes. Small efforts like composting or making double-sided copies could make noticeable differences in the reduction of these two categories.

Efforts to reduce waste are possible in the home, at school, and in the workplace. Even if organized recycling efforts are not available, people everywhere can reduce waste by making simple changes every day.

Reuse

Reuse means using a product again for the originally intended purpose. Reusing items also contributes to the "reduce" principle. Reusing reduces the need to purchase a newer version of an item or product. A simple understanding of supply and demand shows that less demand equals less supply/production. By reducing the need for new products there is less impact on the environment from manufacturing processes as well as less garbage in the land fill. It is a win-win!

Here are some creative ways to reuse items:

- Using a refillable beverage container. (Note: be sure to purchase a "BPA free" product.)
- Store emergency water in green two-liter soda bottles. (Note: Not all types of plastic are recommended for long-term storage or reuse because of deterioration. Be sure your bottles have a number 1 or 2 on them, certifying approval by the Federal Drug Administration (FDA) for use with food/beverage products. Rotate home water storage every 12-18 months.)
- Switch out plastic baggies for plastic containers that can be washed and reused.
- Buy an artificial Christmas tree.
- Use plastic grocery bags as trash bags for small trash cans.
- Purchase/make reusable grocery bags.
- Donate clothing, furniture, and other household goods to charity or others in need.

Repurpose

The word "repurpose" takes on a combination of the terms reuse and recycle and brings a creative flare to the mix. Another term referring to this type of use is "upcycle." Repurpose literally means give an item a new purpose whereas reusing something utilizes the product in its original intended form (container = container, etc.). When repurposing, a container could become a decorative wall hanging or a wall hanging could become a container—the possibilities are endless! Repurposing is a popular way for youth and adults to engage creativity in environmental awareness. A simple internet search will result in hundreds, if not thousands, of ideas to repurpose items and give them a fresh, new, creative use.

Here are a few repurposing ideas:

- Faux metal art from toilet paper tubes (search http://suzyssitcom.com for a free tutorial).
- Pen holder from phone book (search "phone book pen organizer" at http://www.chicaandjo.com) .
- Grocery bags from t-shirts, pet food bags, crocheted/knitted "plarn": "yarn" made from plastic bags (search http://tipnut.com for "reusable grocery bags").

Recycle

The Environmental Protection Agency (EPA) defines recycling as follows: "Residential and commercial recycling turns materials and products that would otherwise become waste into valuable resources. Materials like glass, metal, plastics, paper, and yard trimmings are collected, separated, and sent to facilities that can process them into new materials or products."

The processing of recyclable materials happens in a variety of ways depending on what is being recycled and what the recycled material becomes. For example, plastic bottles are cleaned, sorted according to type (numbers 1-7), and shredded. The shredded plastic is heated to a specific temperature hot enough that the plastic can be formed into small pellets. Manufacturing companies purchase the pellets from plastic recyclers to make a myriad of "new" products from carpet and backpacks to decking and playground equipment.

Another unique recycling process happens with paper. At a recycling mill, paper goes into a large container similar to a household blender. The addition of water in the mixing process turns the paper into a pulp. Depending on the "new" end product, non-recycled paper may be added before manufacturing is complete. Products containing recycled paper range from paper backing on roofing shingles to toilet paper and kitty litter.

Here are other examples of products made using recycled materials:

- Glass: new glass bottles/jars, fiberglass, sand for road work/winter traction.
- Plastic bottles: sleeping bags/ski jackets insulation, polar fleece fabric, Frisbees, new plastic bottles and containers.
- Paper/cardboard: new cardboard, sheetrock, new paper, paper towels, egg cartons, phone books, building insulation, paper plates.
- Metal/aluminum cans: new aluminum cans, bike/car parts, appliances.

Conclusion

Understanding words related to “going GREEN” can be helpful when making consumer decisions. Individuals, families, businesses, and organizations can make important impacts by taking simple steps to reduce, reuse, repurpose, and recycle.”

Sources

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Government of Canada, 2021

Zero plastic waste: the need for action

Plastic is a valuable material and resource because of its unrivalled functionality, durability and low cost. We use plastics in almost all aspects of our lives. In Canada, plastic production is a $35 billion industry employing close to 100,000 people in nearly 2,000 businesses that make and recycle plastic products.

Yet every year Canadians throw away over 3 million tonnes of plastic waste from our homes and businesses. Almost half of that is packaging. The rest comes from sectors like construction, textiles, agriculture, automotive and electronics.

The way we currently use and manage plastics affects our ecosystems and wildlife, and burdens our economy. It is time to shift towards a more resource efficient and circular economy for plastics.

Protecting our environment from marine litter

Marine litter is solid waste that has been discarded, disposed of or littered into the environment, including our freshwater and marine ecosystems. Most of it - about 80% to 90% - is plastic. It comes in all shapes and sizes including microplastics – small plastic particles less than or equal to 5mm in size - and consists of items like fishing gear and packaging.

In 2016, about 29,000 tonnes of plastic waste was littered into our environment in Canada – that is as heavy as almost 300 Blue Whales! Close to 10,000 tonnes of plastics enter the Great Lakes every year from Canada and the United States. Litter that you see on the sidewalk can be blown into a river or lake, or go down the storm drain and end up in the ocean. Marine litter can have many affects. It can transfer contaminants, damage habitats, impact fisheries or seriously harm wildlife if it is ingested or they become entangled in it.

Over the last 25 years, nearly 800,000 volunteers have removed over 1.3 million kilograms of trash from across Canada's shorelines through the Great Canadian Shoreline Cleanup. The most commonly littered items on our shorelines are single-use or short-lived products, many containing plastics such as:

- cigarette butts
- tiny plastic or foam
- food wrappers
- bottle caps
- paper materials
- plastic bags
- beverage cans
- plastic bottles
- straws
- other packaging
- foam
- coffee cups

Building a circular economy

Currently the way we manage plastics is based on a “take-make-waste” model - we extract resources, we make products and then we throw them away. If current trends continue, the plastics thrown away in Canada will be worth $11 billion by 2030.

In a circular economy, the lifecycle of materials and products is extended as long as possible. It follows a “make-use-return” model so that materials and products are reused, repaired, re-manufactured or recycled. By creating a circular economy for plastics, we could:

- reduce plastic and carbon pollution
- generate billions of dollars in revenue
- create as many as 42,000 jobs by 2030.

Our vision is a zero plastic waste future where plastics stay in the economy and out of landfills and the environment.

Zero plastic waste: Canada’s actions

The Government of Canada is working with all levels of government, industry, non-government organizations, academia and Canadians to take action on plastic waste and pollution.

Ocean Plastics Charter

Under Canada’s G7 presidency in 2018, we championed the development of the Ocean Plastics Charter to move toward a more sustainable approach to producing, using and managing plastics. By signing onto the Charter, governments, businesses and organizations join us in committing to a more resource-efficient and lifecycle approach to plastics stewardship, on land and at sea. Through these partnerships, we can grow the momentum for real action on plastic pollution around the world.

Ocean Plastics Charter

Canada-wide Strategy on Zero Plastic Waste

In November 2018, through the Canadian Council of Ministers of the Environment, the federal, provincial and territorial governments approved in principle a Canada-wide Strategy on Zero Plastic Waste. Building on the Ocean Plastics Charter, the strategy takes a circular economy approach to plastics and provides a framework for action in Canada.

We continue to work together to achieve results in key areas of the strategy:

- product design
- single-use plastics
- collection systems
- markets
- recycling capacity
- consumer awareness
- aquatic activities

- research and monitoring
- clean-up
- global action

The federal, provincial and territorial governments also adopted a Canada-wide Action Plan on Zero Plastic Waste to implement the Strategy. This plan sets out tangible actions and clear timelines to better prevent, reduce, reuse, recover, capture and clean up plastic waste and pollution in Canada.

These actions will help Canada reduce plastic pollution, create economic opportunities to recover the value of used plastics and achieve our goal of zero plastic waste by 2030.

Canada-wide Strategy on Zero Plastic Waste (PDF)

Canada-wide Action Plan on Zero Plastic Waste Phase 1 (PDF)

Canada-wide Action Plan on Zero Plastic Waste Phase 2 (PDF)

Policies and regulations

The Government of Canada has over 10 federal acts, regulations and agreements that prevent plastic waste and marine litter. In June 2017, the Microbeads in Toiletries Regulations were published which prohibit the manufacture, import and sale of toiletries containing plastic microbeads, including non-prescription drugs and natural health products.

In June 2019, we announced new federal efforts to help meet our commitments in the Ocean Plastics Charter and the Canada-wide Strategy on Zero Plastic Waste. This included addressing single-use plastics and working with provinces and territories to make producers responsible for the plastic waste that their products generate.

On October 7, 2020, we announced proposed next steps to achieve the goal of zero plastic waste by 2030. One element of the approach is the proposal to ban or restrict the use of certain single-use plastics where there is evidence that they are found in the environment, are often not recycled, and have readily available and viable alternatives. This could include items such as plastic bags, straws, stir sticks, beverage carriers, cutlery, and food ware made from problematic plastics. The approach also proposes improvements to recover and recycle plastic, so it stays in our economy and out of the environment. The announcement included the release of a discussion paper that outlines the proposed approach for public comment.

From October to December 2020, Environment and Climate Change Canada engaged with Canadians and stakeholders on its proposed Integrated Management Approach to Plastic Products discussion paper by hosting a series of engagement webinars. These webinars provided an overview of the proposed Integrated Management Approach and discussed in more details the proposed Management Framework for Single-use Plastics and the importance of establishing performance standards for plastic products as well as ensuring sound end-of-life responsibility. In August 2021, a What We Heard report was published that summarizes the feedback received on the discussion paper via written comments, the webinars and stakeholder discussion sessions.

In May 2021, “plastic manufactured items” was added to Schedule 1 to the Canadian Environmental Protection Act, 1999 (CEPA). This means that the Government of Canada can take regulatory and other action in support of reaching Canada’s zero plastic waste goal and setting the conditions for a plastics circular economy. Feedback received is being considered in developing proposed regulations to ban or restrict certain single-use plastics, and in developing proposed recycled content requirements.

Microbeads in Toiletries Regulations

Canada to ban harmful single-use plastics and hold companies responsible for plastic waste

Canada one-step closer to zero plastic waste by 2030

A proposed integrated management approach to plastic products: discussion paper

What We Heard Report: A proposed integrated management approach to plastic products to prevent waste and pollution

Canada Gazette, Part II, Volume 155, Number 10: Final Order Adding plastic manufactured items to Schedule 1 to the *Canadian Environmental Protection Act, 1999*

Plastic pollution

Greening our government

Canada is driving action within the federal government and taking practical steps to manage the use and disposal of plastics within our own operations. In 2018, we set goals to:

- divert at least 75% of plastic waste from federal operations by 2030
- eliminate the unnecessary use of single-use plastics in government operations, meetings and events
- purchase more sustainable plastic products that can be reused, recycled, repaired or repurposed.

Greening Government Strategy

Government of Canada actions on plastic waste in federal operations

Retaining product value

As part of our work to facilitate the transition to a circular economy and reduce plastic waste and pollution, the Government of Canada will develop a national strategy to encourage the remanufacturing of products and other value-retention processes – VRPs – (such as refurbishment, repair and reuse).

As a first step, a socio-economic and environmental study looking at six industry sectors was published in June 2021. The study provides baseline data on VRPs in Canada and evaluates the benefits, challenges and opportunities of increasing VRPs in Canada. These findings will help inform the development of a national strategy and contribute to Canada's comprehensive zero plastic waste agenda. We are seeking your feedback on the study and your preliminary ideas on elements that could be considered as part of a national strategy. You can provide your comments by August 30, 2021. More information on the comment period is available here: Comments on: Environmental and socio-economic study on remanufacturing and other value-retention processes in Canada.

Retaining product value in a circular economy
Socio-economic and environmental study on the remanufacturing sector and other value-retention processes in Canada (full study and executive summary)

Advancing science

World-class, robust science informs evidence-based decisions, spurs innovation and helps to track progress. We support and conduct research that improves our understanding of the plastics economy in Canada. This includes the sources, distribution, fate and impacts of plastic pollution and microplastics in the environment and wildlife. But we still need to expand research, coordinate activities, support information sharing, and fill key research gaps.

Canada's Plastics Science Agenda (CaPSA), released in July 2019, is a framework to inform future science and research investments, as well as decision-making. It identifies areas where knowledge gaps need to be filled, such as for:

- detecting plastics in the environment
- understanding and mitigating potential impacts on wildlife, human health and the environment and,
- advancing sustainable plastic production, recycling and recovery.

CaPSA was informed by two November 2018 events with subject matter experts: the Best Brains Exchange on the Ecological and Human Health Fate and Effects of Microplastic Pollution, and the Canadian Science Symposium on Plastics.

In 2020, we launched two initiatives to fund priority research areas. This includes the Increasing Knowledge on Plastics Pollution Initiative, which is providing funding for 16 research projects to be completed by March 2022. It also includes the Plastics Science for a Cleaner Future, which will fund projects up to $1 million over 4 years.

In October 2020, we published the Final Science Assessment of Plastic Pollution. This report reviews the available scientific information regarding the potential impacts of plastic pollution on the environment and human health. It recommends action to reduce plastics in the environment in keeping with the precautionary principle. It will also help inform federal actions and policies, as well as future research on plastic pollution in Canada.

Canada's Plastic Science Agenda

The Government of Canada invests in research on plastic pollution in our environment

Plastics science for a cleaner future

Science assessment of plastic pollution

Plastics innovation

We have pledged $20 million in support of the G7 Innovation Challenge to Address Marine Plastic Litter. It will provide the incentive to develop innovative social or technological solutions for the more sustainable management of plastics throughout their lifecycle.

The Canadian Plastics Innovation Challenges are part of Canada's comprehensive approach to addressing plastic waste and pollution. This program provides funding to small and medium-sized enterprises to incentivize the development of technology to address plastic waste. Through the Canadian Plastics Innovation Challenges, the government is investing nearly $19 million to support Canadian innovators to develop solutions for plastics challenges, by providing winners with up to $150,000 to develop a proof of concept and subsequently up to $1 million to develop a prototype if selected.

G7 innovation challenge to address marine plastic litter

Innovation Solutions Canada – Challenges

Government of Canada supports innovative, made-in-Canada solutions to plastic waste

Government of Canada supports small businesses developing innovative solutions to plastic pollution

Canada unveils support for Canadian innovation by small businesses to reduce plastic waste and beat plastic pollution

Mobilizing Canadians

We are working with all levels of government, industry, organizations and communities to implement plastic waste solutions. Since 2018, we have invested over $5 million in education and awareness-raising activities, citizen science, and community projects and clean-ups. These efforts help mobilize and engage Canadians to reduce plastic waste and pollution.

Through the Zero Plastic Waste Initiative, we are supporting new innovative solutions that prevent, capture and remove plastic pollution and inform sustainable consumer actions. We are also supporting industry in developing solutions for a circular plastics economy.

Canada's $8.3 million Sustainable Fisheries Solutions and Retrieval Support Contribution Program, or Ghost Gear Fund, is assisting fish harvesters, environmental groups, Indigenous communities, the aquaculture industry, and coastal communities to find and retrieve harmful ghost gear from the ocean and dispose of it responsibly so that it can be recycled back into the economy. In 2020, 63 tonnes – the equivalent of 11 elephants – of lost or discarded fishing gear was retrieved from Atlantic Canada. The gear retrieved came from a combination of projects: the Ghost Gear Fund, self-funded third-party projects authorized to collect gear, fishery officer patrols, and fish harvesters.

We also asked Canadians to share their ideas about how we can reduce plastic waste and marine litter. Between April and September 2018, we received over 1,900 comments on the online platform and over 12,000 campaign letters and emails in response.

Zero Plastic Waste Initiative

New projects funded by the Zero Plastic Waste Initiative

The Ghost Gear Fund in action

Moving Canada toward zero plastic waste: Closed consultation

International actions

Canada participates in several international organizations advancing policy and research to reduce plastic waste and marine litter such as the G7, the G20, the Arctic Council and various bodies under the United Nations. We also participate in a variety of initiatives and measures including:

- Arctic Council Desktop Study on Marine Litter including Microplastics in the Arctic
- Commission for Environmental Cooperation: Reducing Marine Litter
- Food and Agriculture Organizations of the United Nations Code of Conduct on Responsible Fishing
- Global Ghost Gear Initiative
- G7 Action Plan to Combat Marine Litter (PDF)
- G7 Bologna Environment Minister's Meeting Communique: 5-year Bologna Roadmap (PDF)
- G7 Toyama Framework on Material Cycles (PDF)
- G20 Action Plan on Marine Litter (PDF)

- G20 Implementation Framework for Actions on Marine Plastic Litter (PDF)

- United Nations Clean Seas Campaign
- United Nations Environment Assembly resolutions
- United Nations Global Partnership on Marine Litter
- United Nations Sustainable Development Goals

Several legally-binding international agreements have been implemented that contribute to preventing plastic waste and marine litter such as:

- The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal
- The International Convention for the Prevention of Pollution from Ships
- The London Convention and Protocol to prevent marine pollution by dumping at sea

As well, we are contributing $100 million to help developing countries prevent plastic waste from entering the oceans, address plastic waste on shorelines, and better manage existing plastic resources. So far, this includes:

- $65 million through the World Bank ProBlue fund
- $6 million to strengthen innovative private-public partnerships through the World Economic Forum's Global Plastic Action Partnership
- $9 million to the Incubation Network to prevent plastic waste from entering the world's oceans
- $20 million to help implement the G7 Innovation Challenge to Address Marine Plastic Litter

Stockholm Biochar Project

June 29, 2018 – Nordregio; Photography by Kari Kohvakka

Managing the increasing amount of waste generated in urban spaces is a common challenge to cities worldwide. Since March 2017, Stockholm has been working to address this problem by opening the first large scale biochar plant. This project reduces carbon emissions while engaging people in the fight against climate change. Residents provide garden waste to the city, which produces biochar – a charcoal-like product that sequester carbon in soil for thousands of years.

Solution

With the help of the city residents and local authorities, garden and park waste are collected and stored in different waste management centers located across Stockholm. Once gathered in the plant, this waste is turned into biochar through a carbonization process. The by-product of the biochar production, pyrolysis gas, generates energy for the city's district heating system.

When delivering garden waste to the management centers, the residents can pick up biochar to use in their gardens. The product is also sold to other local authorities to be used to grow plants and trees in parks and public spaces of the city.

Using biochar in green areas of the city, carbon sinks, plants grow easily, and storm water infiltrates efficiently, helping to manage flooding. Furthermore, a greener city contributes with a whole array of auxiliary benefits such as cleaner air, increased biodiversity while combating heat island effects.

Outcome

Four additional biochar plants are planned to be completed in the following years. These five plants are expected producing 7 000 tons of biochar by 2020, sequestering 25 200 tons of CO_2 (the equivalent of taking 3 500 cars off the road) and producing corresponding 25 200 MW/hour of energy (the equivalent of heat for 400 apartments). Within eight years the project will deliver a revenue on the city's investment estimated approximately over 854 000 EUR.

While there are examples of biochar use across Europe, Stockholm implemented the first large-scale plant with the collaboration of local authorities and residents in the generation of the product. The project is one of the winners in the 2014 Mayors Challenge, which is a competition for cities held by Bloomberg Philanthropies.

Potentials

Stockholm City has received many requests from other cities and organisations that are interested in replicating the program. As a result, the Biochar team has published a replication manual and checklist for reference.

Investigations are already underway into how to develop this system using other kinds of waste (e.g. by-products from forestry and agriculture, straw, sewage sludge and horse manure) and to extend the use of biochar to other applications (e.g. building materials).

Sustainable Materials Management: Non-Hazardous Materials and Waste Management Hierarchy

US EPA, 2021

EPA developed the non-hazardous materials and waste management hierarchy in recognition that no single waste management approach is suitable for managing all materials and waste streams in all circumstances. The hierarchy ranks the various management strategies from most to least environmentally preferred. The hierarchy places emphasis on reducing, reusing, and recycling as key to sustainable materials management.

Source Reduction and Reuse

Source reduction, also known as waste prevention, means reducing waste at the source, and is the most environmentally preferred strategy. It can take many different forms, including reusing or donating items, buying in bulk, reducing packaging, redesigning products, and reducing toxicity. Source reduction also is important in manufacturing. Lightweighting of packaging, reuse, and remanufacturing are all becoming more popular business trends. Purchasing products that incorporate these features supports source reduction.

Source reduction can:

- Save natural resources,
- Conserve energy,
- Reduce pollution,
- Reduce the toxicity of our waste, and
- Save money for consumers and businesses alike.

Recycling and Composting

Recycling is a series of activities that includes collecting used, reused, or unused items that would otherwise be considered waste; sorting and processing the recyclable products into raw materials; and remanufacturing the recycled raw materials into new products. Consumers provide the last link in recycling by purchasing products made from recycled content. Recycling also can include composting of food scraps, yard trimmings, and other organic materials.

Benefits of recycling include:

- Preventing the emission of many greenhouse gases and water pollutants;
- Saving energy;
- Supplying valuable raw materials to industry;
- Creating jobs;
- Stimulating the development of greener technologies;
- Conserving resources for our children's future; and
- Reducing the need for new landfills and combustors.

Energy Recovery

Energy recovery from waste is the conversion of non-recyclable waste materials into useable heat, electricity, or fuel through a variety of processes, including combustion, gasification, pyrolization, anaerobic digestion, and landfill gas (LFG) recovery. This process is often called waste-to-energy (WTE). Converting non-recyclable waste materials into electricity and heat generates a renewable energy source and reduces carbon emissions by offsetting the need for energy from fossil sources and reduces methane generation from landfills. After energy is recovered, approximately ten percent of the volume remains as ash, which is generally sent to a landfill.

Treatment and Disposal

Prior to disposal, treatment can help reduce the volume and toxicity of waste. Treatments can be physical (e.g., shredding), chemical (e.g., incineration), and biological (e.g., anaerobic digestor). Landfills are the most common form of waste disposal and are an important component of an integrated waste management system. Modern landfills are well-engineered facilities located, designed, operated, and monitored to ensure compliance with state and federal regulations. Landfills that accept municipal solid waste are primarily regulated by state, tribal, and local governments. EPA, however, established national standards that these landfills must meet in order to stay open. The federal landfill regulations eliminated the open dumps (disposal facilities that do not meet federal and state criteria) of the past. Today’s landfills must meet stringent design, operation, and closure requirements. Methane gas, a byproduct of decomposing waste, can be collected and used as fuel to generate electricity. After a landfill is capped, the land may be used for recreation sites such as parks, golf courses, and ski slopes.

03. Food waste in America

Key Topic 3: What is Food Waste and How Does it Affect Us?

1. Identify and explain waste classified as food waste and what can be repurposed.

Study Resources

Food Waste in America: Facts and Statistics- *Rubicon, 2020*

Food Waste - *University of Illinois Urbana-Champaign, 2021*

By: Ryan Cooper, Waste Diversion Manager and Organics Recycling Lead August 25, 2020

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Food Waste in America: Facts and Statistics

Food waste in America has skyrocketed in recent years, with 103 million tons (81.4 billion pounds) of food waste generated in 2018, according to the Environmental Protection Agency (EPA); the equivalent of over 450,000 Statue of Liberties.

This is a shocking statistic which unfortunately becomes less surprising the more you learn about the growing problem of food waste in America.

Globally, we waste a third of all food produced for human consumption, according to the Food and Agriculture Organization (FAO) of the United Nations (UN). In the United States, that equates to approximately one pound of food wasted per person per day. If we keep this up, reports estimate that in ten years, we'll waste the equivalent of 66 tons of food per second across the globe.

What is Food Waste?

Before we go any further, here's a quick primer on the basics of food waste:

Rubicon's mission is to end waste, in all of its forms. In this article, we're going to look at the issues surrounding food waste in the U.S. compared to the rest of the world. We're going to look at what causes food waste at every level of the food supply chain; and how to reduce it. And we're going to uncover the most interesting food waste statistics out there.

Keep reading to learn more about food waste in America.

How Much Food is Wasted in America?

Each day in the United States approximately one pound of food per person is wasted. This equates to 103 million tons (81.4 billion pounds) of food waste generated in America in 2017, or between 30-40 percent of the food supply, according to the United States Department of Agriculture (USDA).

How much food is wasted in the U.S. can be seen directly through its monetary losses. The annual food waste in America has an approximate value of $161 billion, while the average American family of four throws out $1,500 in wasted food per year.

As it stands, the U.S. is the worldwide leader in food waste generation, with the majority of wasted food being sent to landfills. In fact, food waste is the number one material in American landfills, accounting for 24.1 percent of all municipal solid waste (MSW) according to the EPA.

How did we get here? Knowing how much food is wasted in America each year is only the first step toward tackling a problem that is bigger than the simple monetary loss. The reality of food waste in America is that we live in a country in which more than 54 million people are food insecure (18 million of which are children) according to 2020 data collected by Feeding America. These numbers are up from 37 million and 11 million, respectively, in 2019, with the sharp rise in food insecurity due to the effects of the COVID-19 public health emergency and the subsequent economic downturn. (For more food waste statistics, scroll down to the "Food Waste Facts and Statistics" section below.)

What Causes Food Waste in America?

The causes of food waste in America go far beyond just tossing our leftovers in the trash, and they are crucial to understand in order to reduce our nation's collective food waste going forward.

From production and supply, to our tendency to overpurchase, to the unrealistic aesthetic standards we have come to expect from our fruits and vegetables, these are the three main causes of food waste in America:

Production and Supply Chain

Food wastage occurs at every step of the supply chain, with different types of foods being more or less likely to be lost at each step.

According to data from the United States, Canada, Australia, and New Zealand that was collected by the Natural Resources Defense Council (NRDC), 20 percent of fruit and vegetables are lost during production, 12 percent are lost at the distribution and retail level, and a further 28 percent are lost at the consumer level. Seafood faces a similar fate, with 11 percent lost during production, 5 percent lost during processing and packaging, 9.5 percent lost at the distribution and retail level, and a further 33 percent lost at the consumer level. (For more on the specifics of food loss, this paper from Dana Gunders is a must-read.)

Unrealistic Aesthetic Standards

When you're in the produce aisle at your local supermarket, do you ever put back carrots, potatoes, zucchinis, or any other fruit or vegetable because it doesn't look as straight, slender, round, or otherwise how we have been conditioned to believe this item should look?

Food waste in America is exacerbated by unrealistic aesthetic standards for our produce. You're not alone in not picking up that misshapen carrot in the produce aisle. Grocery stores have learned over time that consumers don't tend to purchase misshapen produce. As a result, many stores stop accepting them from their suppliers. Thankfully there are outlets for misshapen produce; restaurants don't care what their carrots look like so long as they can turn them into delicious dishes on the plate, and start-ups such as Imperfect Foods, Misfits Market, and Hungry Harvest make it easy for consumers to receive "ugly produce" right to their door.

Portion Sizes and Overpurchasing

While not the most dramatic cause of food wastage, increased portion sizes in schools, restaurants, and the home leads to overpurchasing. Subsequently, more food is thrown out because it's gone bad.

Restaurants want to have enough food to serve their customers, so they overbuy and throw out what goes bad. At the consumer level, however, you have the power to ensure you purchase only what you need, you serve portion sizes that work for you and your family, and you don't throw out food too early.

What are the Effects of Food Waste?

While the negative effects of food waste in America are numerous, this article will focus on the three largest.

Environmental Impact

The environmental impact of food waste in America cannot be undersold. As food rots in a landfill, it emits methane, a greenhouse gas 28 to 36 times more potent than the carbon that comes out of passenger vehicles.

Landfills are the third-largest industrial emitter of methane, with food waste alone representing 8 percent of total global greenhouse gas (GHG) emissions. While it is possible to offset the harm of these emissions through organics recycling, composting, and anaerobic digestion, the best way to reduce these emissions is to waste less food in the first place.

Food Insecurity and Global Hunger

While mentioned above, it bears repeating here. We live in a country in which more than 54 million people are food insecure (18 million of which are children) according to 2020 data collected by Feeding America, meaning they lack reliable access to a sufficient quantity of affordable, nutritious food. These numbers are up from 37 million and 11 million, respectively, in 2019, due to COVID-19.

The fact that we as a country are wasting 30-40 percent of the food supply each year when more than 54 million Americans are food insecure is unconscionable.

Wasted Natural Resources

While rotting food in our country's landfills causes harm to our environment after it is wasted, allowing perfectly good food to go to waste is also wasteful of the natural resources that helped this food come to fruition in the first place.

When we waste food, we waste the water, energy, and physical labor it took to produce, package, and ship this food. We waste the fuel that was used to transport this food from one part of the country to another. When we waste food, it's not just the food itself that is being wasted.

How to Reduce Food Waste in America

Reducing food waste in America is going to take some time. Highlighting food waste statistics and facts, such as those below, is a good way to help get the word out about this ever-growing problem, but our work can't stop there.

As we just learned, there's more to food waste than what we do and don't eat. We're wasting $161 billion annually (with the average American family of four throwing out $1,500 in wasted food per year) while depleting our natural resources, harming our environment, and wasting food that the more than 54 million food insecure people in the United States could benefit from.

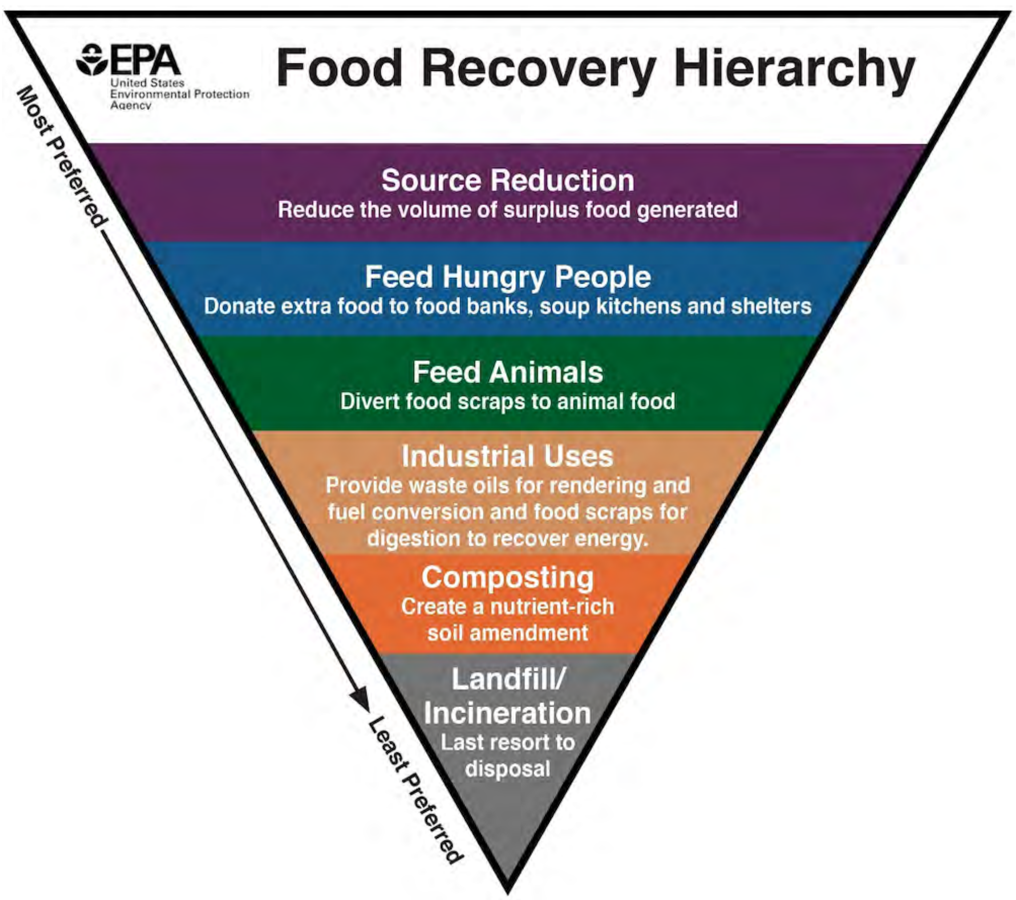
Here are some ideas for what you can do to reduce food waste in America:

- Put together a detailed shopping list before you go to the grocery store by planning your meals in advance—and avoid impulse purchases.
- Take leftover containers to restaurants. While some don't provide takeout containers, they would be hard-pressed to stop you from using your own.

- Recognize that while your eyes may be bigger than your stomach, your plate doesn't have to be. Using smaller plates can help you to properly portion your food.
- Don't be afraid of an emptier fridge. When you can't see the food you have purchased, you're more likely to forget about it and let it rot.
- Keep track of the food you're throwing away the most to cut down on trends. Add a dollar sign value so you can see the impact it has on your budget.
- Expiration dates are misleading and nonstandardized, leading many to toss out perfectly good food. Trust your sense of smell, and your gut, before throwing items away.
- Read the EPA's "Too Good to Waste" implementation guide and toolkit to reduce wasteful food management practices.

The Food Recovery Hierarchy

When we talk about reducing food waste in America we would be remiss to not mention the Food Recovery Hierarchy.



Developed by the EPA, the Food Recovery Hierarchy prioritizes actions businesses and individuals alike can take to prevent and divert wasted food. As you can see, source reduction, or simply purchasing less food in the first place, is number one. This is followed by food donations to those in need, sending food scraps to animal feed, then industrial uses including anaerobic digestion and ethanol facilities, before moving on to composting.

Hopefully, food waste is never landfilled because it has so many beneficial uses.

Food Waste Facts and Statistics

The following food waste facts and statistics tell the story of food waste in America.

As I noted earlier on in this article, reading food waste statistics that tell us just how much food is wasted in America on an annual basis is a good way to help get the word out about the problem of food wastage in this country—but we must go further to reduce food waste at every level of the food supply chain.

If you are a restaurant owner looking to implement food waste reduction programs, or you're a business owner looking to run a more sustainable business, reach out to Rubicon's Sustainability team at sustainability@rubicon.com and we will be happy to help.

Without further ado, here are 20 of the most interesting food waste facts and statistics:

. 103 million tons (81.4 billion pounds) of food waste was generated in the United States in 2018, the equivalent of over 450,000 Statue of Liberties.
. An estimated 1.3 billion tonnes of food is wasted globally each year, one third of all food produced for human consumption.
. In ten years, the United States will waste the equivalent of 66 tons of food per second across the globe.
. If food waste was a country, it would be the third largest emitter of greenhouse gas emissions in the world after the United States and China.
. The United States wastes 30-40 percent of its food supply each year.
. The annual food waste in America has an approximate value of $161 billion.
. The average American family of four throws out $1,500 in food per year.
. Food waste is the number one material in America's landfills, accounting for 24.1 percent of all municipal solid waste (MSW).
. More than 54 million people are food insecure (18 million of which are children) according to 2020 data, accounting for one in six people. These numbers are up from 37 million and 11 million, respectively, in 2019, due to COVID-19.
. Approximately 38 percent of grain products are lost, 50 percent of seafood, 52 percent of fruits and vegetables, 22 percent of meat, and 20 percent of milk.
. As food rots in a landfill, it emits methane, a greenhouse gas 28 to 36 times more potent than the carbon that comes out of passenger vehicles.
. Food waste represents 8 percent of total global greenhouse gas emissions.
. Only 6.3 percent of food waste in America was composted in 2017.
. The healthier you eat, the more important it is that you stay on top of your consumption. If you buy perishable food in bulk, such as fruits, vegetables, and meat, organize your refrigerator so what you need to eat first is up front and visible.
. Americans discard approximately 35 percent (204 million pounds) of edible turkey meat each year, the majority after the Thanksgiving holiday.
. Food is often safe to eat even after it "expires." Expiration dates are misleading and nonstandardized, leading many to toss out perfectly good food.

. Global preferences for a western diet consisting of a high intake of carbohydrates, sugar, and sodium are major contributors to environmental burdens such as greenhouse gas emissions and land use.
. Shrink wrapping produce helps to reduce food waste by increasing its shelf life. But remember to recycle the shrink wrap and other plastic bags, wraps, and filmthat are clean and dry.
. Lack of awareness of basic nutrition adds to food waste among consumers. While many people believe it's better to buy fresh food, in reality, frozen food products often retain more nutrients while lasting longer.
. The size of your refrigerator can impact the amount of food you waste. You're more likely to forget about food you have, improperly store your food, and buy more than you can eat before it goes bad.

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To learn more about Rubicon's work transforming the entire category of waste and recycling, be sure to download our inaugural Environmental, Social, and Governance (ESG) Report.

If you have any questions about food waste in America, or any of the food waste facts and statistics on this page, you can reach out to Rubicon's Sustainability team directly at sustainability@rubicon.com, or contact our sales team at (844) 479-1507.

Ryan Cooper is a Waste Diversion Manager and the Organics Recycling Lead at Rubicon. To stay ahead of Rubicon's announcements of new partnerships and collaborations around the world, be sure to follow us on LinkedIn, Facebook, and Twitter, or contact us today.

Sources: 1, 7, 8, 11, 13, 20) Environmental Protection Agency (EPA); 2, 12) Food and Agriculture Organization (FAO); 3, 19) Boston Consulting Group (BCG) Henderson Institute; 4) World Resources Institute; 5, 10) Natural Resources Defense Council (NRDC); 6) U.S. Food and Drugs Administration; 9) Feeding America; 14) Municipal Waste Association; 15) Waste Dive; 16) Reuters; 17) United States Department of Agriculture (USDA); 18) Australian Broadcasting Corporation (ABC) News.

Food Waste

Try these easy tips to reduce food waste.

Eating Tips

- Join the "ugly" food movement and shop for the fun shapes foods can take on.
- Have you ever used broccoli stalks or the green tops of beets? Find ideas in cookbooks and from MSU Extension's Are you throwing away valuable food?
- Cooking less can be a challenge for empty nesters and small households. Check out the "Cooking for 1 or 2" lesson from NDSU Extension.
- Planning to eat leftovers for future meals is a great way to reduce food waste. Not all leftovers reheat well, so pick recipes that do. Remember, eat leftovers within 3-4 days.
- What is your favorite way to organize the refrigerator, freezer, or pantry? Check out ISU Extension's *The Basics of Kitchen Organization* for tips.
- Notice how much food gets discarded during holidays, birthdays, and office parties. Serve less food, try a no-food event, or use your food waste knowledge to try something else.
- Eat the skins on produce to reduce food waste, consume more nutrients, and spend less time peeling fruits and veggies.

Eating Out Tips

- Reduce food waste while dining out! Order lunch portions or take home part of your meal for leftovers.
- Restaurants often serve very large portions. Share to limit food waste – and have fun with your dining companion.
- Not a fan of potato salad that your meal comes with? Ask about swapping it for a side you will enjoy. Don't eat tomato and lettuce on your sandwich? Let your server know to leave it off.

Food Safety Tips

- That can of black beans you lost in the back of the pantry might still be good quality and safe to eat. Learn more at fsis.usda.gov (http://fsis.usda.gov) and stilltasty.com (http://stilltasty.com).
- Whether a short or long power outage, find out which foods can be saved and which ones need to be thrown out.
- Not sure how long to keep food, or the best way to store it for longer shelf life? Use technology to answer your questions with "Save the Food" Skill on your smart speaker.

Prolong Food Life

- Preserving is great for that extra pound of fresh green beans you bought! Learn more about preserving options from the National Center for Home Food Preservation (http://nchfp.uga.edu).
- Did you not use that whole can of pumpkin puree? Or all that bottled salsa? No worries – your freezer can help.
- Foods can have a long life. Learn more about food donations and food recovery from USDA at udsa.gov (http://udsa.gov) and EPA at epa.gov (http://epa.gov).
- See storage recommendations from NDSU Extension for fruits and veggies at ag.ndsu.edu (http://ag.ndsu.edu).
- Refrigeration and freezing keep foods safe longer by delaying food decay and limiting most microbial growth.
- When putting foods away, move them around so foods that are closer to "best-by" dates are in front. This way you are more likely to use them.
- Turn old and overripe produce into something new. Overripe bananas are great in banana bread. Soft, mealy apples make great applesauce or apple crisp.

Shopping Tips

- Habits take time to build, including checking your kitchen food inventory before going shopping. What helps you remember to check before you shop?
- Shop local farmers markets, roadside stands, and CSAs to buy just the amount you want.

Food Waste Usage

- From traditional compost to vermicompost, use the nutrients in your leftover scraps to make plant food.
- Start the conversation about where your food goes after trash pickup. Hint, it's usually a landfill.
- From municipal groups to universities to commercial waste disposal, check your local area for community composting.
- Learn more about the Food Recovery Hierarchy from the Environmental Protection Agency at epa.gov.
- Try out EPA's "Too Good to Waste" Challenge at epa.gov. Find out how much you waste at home and how to waste less.
- Reducing single-use packaging and food waste go hand in hand. Apply your food waste knowledge, and add in reusable packaging, like grocery totes or produce bags. Try making your own with upcycled materials!

TOPICS

Illinois Extension

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Urbana, IL 61801

Phone: 217-333-5900

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04. Composting and Food Waste

Current Environmental Issue Study Resources

Key Topic 4: Composting and Food Waste

1.Describe composting processes and identify how composting supports waste diversion efforts.
2.Explain how composting improves soil health and provide evidence for how composting supports water conservation efforts.
3.Describe the problem of food waste and explain how it impacts the sustainability of the global food supply.

Study Resources

Composting 101 - *Natural Resources Defense Council, 2020*
Farmers lead composting revolution to heal African soils- *Fernando Naves Sousa, The Ecologist 2014*
Composting - *USDA-NRCS, 1998*
Wasting Food Just Feeds Climate Change - *United Nations, 2021*

Composting 101

Recycling food and other organic waste into compost provides a range of environmental benefits, including improving soil health, reducing greenhouse gas emissions, recycling nutrients, and mitigating the impact of droughts.

July 20, 2020
Shelia Hu

Jump to Section

What Is Composting?

Composting is the natural process of recycling organic matter, such as leaves and food scraps, into a valuable fertilizer that can enrich soil and plants. Anything that grows decomposes eventually; composting simply speeds up the process by providing an ideal environment for bacteria, fungi, and other decomposing organisms (such as worms, sowbugs, and nematodes) to do their work. The resulting decomposed matter, which often ends up looking like fertile garden soil, is called compost. Fondly referred to by farmers as “black gold,” compost is rich in nutrients and can be used for gardening, horticulture, and agriculture.

Organic discards can be processed in industrial-scale composting facilities, in smaller-scale community composting systems, and in anaerobic digesters, among other options. This guide focuses primarily on home composting, which is a great way to keep your organic discards out of the waste stream and produce a valuable soil amendment for your own use.

Benefits of Composting

Reduces the Waste Stream

Composting is a great way to recycle the organic waste we generate at home. Food scraps and garden waste combined make up more than 28 percent of what we throw away. Not only is food waste a significant burden on the environment, but processing it is costly. The average cost to landfill municipal solid waste in the United States was around $55 per ton in 2019. With the United States generating more than 267 million tons of municipal waste in 2017 and sending two-thirds of that to landfills and incinerators, we spent billions of dollars on waste management. Composting at home allows us to divert some of that waste from landfills and turn it into something practical for our yards.

Cuts Methane Emissions From Landfills

Typically when organic matter decomposes, it undergoes aerobic decomposition, meaning that it's broken down by microorganisms that require oxygen. When compostable waste goes to a landfill, it gets buried under massive amounts of other trash, cutting off a regular supply of oxygen for the decomposers. The waste then ends up undergoing anaerobic decomposition, being broken down by organisms that can live without free-flowing oxygen. During anaerobic decomposition, biogas is created as a by-product. This biogas is roughly 50 percent methane and 50 percent carbon dioxide, both of which are potent greenhouse gases, with methane being 28 to 36 times more effective than CO_2 at trapping heat in the atmosphere over a century. Although most modern landfills have methane capture systems, these do not capture all of the gas; landfills are the third-largest source of human-generated methane emissions in the United States.

Because our solid waste infrastructure was designed around landfilling, only about 6 percent of food waste gets composted. However, states, cities, and individual businesses and vendors can spearhead zero-waste strategies to increase composting and recycling rates within their jurisdictions and to keep waste from being generated in the first place. There have been many composting success stories around the country, one notable example being San Francisco. In 1996 San Francisco established a large-scale composting program, and by 2000 it was able to divert 50 percent of its wastefrom landfills. By increasing its goals over the years, San Francisco has been diverting more than 80 percent of waste from landfills since 2012. That means more than 90,000 metric tons of carbon emissions are avoided each year—equivalent to the annual greenhouse gas emissions from 20,000 passenger vehicles.

Improves Soil Health and Lessens Erosion

Compost is an essential tool for improving large-scale agricultural systems. Compost contains three primary nutrients needed by garden crops: nitrogen, phosphorus, and potassium. It also includes traces of other essential elements like calcium, magnesium, iron, and zinc. Instead of relying on synthetic fertilizers that contain harmful chemicals, composting offers an organic alternative. Research has shown the capability of compost to increase soil's water retention capacity, productivity, and resiliency.

Conserves Water

Agriculture is a major consumer of water in the United States, accounting for approximately 80 percent of the nation's water use. Irrigation systems are effective but are expensive and time-consuming for farmers to manage. Additionally, water is becoming increasingly difficult to obtain across the country.

How can compost help? Research has shown the water-retaining capacities of soil increase with the addition of organic matter. In fact, each 1 percent increase in soil organic matter helps soil hold 20,000 gallons more water per acre. By using compost to foster healthy soil, farmers do not have to use as much water and can still have higher yields compared with farming with degraded soil.

Reduces Personal Food Waste

Consumers are responsible for a staggering amount of wasted food. An average American family of four throws out about $150 worth of food per month, a 50 percent increase since the 1970s. NRDC research in three U.S. cities indicated that the category of edible food most wasted by households was fruits and vegetables. According to a 2016 report in *The Guardian*, U.S. retailers and consumers throw away about 60 million tons (or $160 billion) worth of produce annually. The best way to reduce impacts from food waste is to prevent waste from occurring in the first place, so NRDC works through its Save the Food campaign and other tools to educate consumers on how to shop for, prepare, and store food to minimize waste. However, even if we do everything possible to decrease food waste, there will still be food scraps that cannot be consumed (e.g., a banana peel). Composting is a great way to recycle those discards instead of tossing them in the trash.

Piotr Malczyk/iStock

Types of Home Composting

Composting can be done both indoors and outdoors and can be as complicated or as simple as you would like. The best way for you to compost at home depends on several factors:

- Where you live/availability of space
- How much organic waste you produce
- What kind of organic waste you produce (kitchen and/or yard waste)
- Amount of time you can spend on the composting process

There are two main types of backyard composting: cold (also known as passive composting) and hot (also called active composting). Cold composting breaks down organic matter slowly, but it also takes the least amount of effort and maintenance. Anything organic decomposes eventually; cold composting is just letting Mother Nature do her job with minimal intervention on your part. You do not need to worry about the ratio of compost ingredients, aerate regularly, or monitor moisture levels. Cold composting is the best process if you have little organic waste to compost and not much time to tend to the process, and if you are not in a hurry for finished compost. However, depending on what kind of cold method you use, it can take one to two yearsbefore you get usable compost. Additionally, a cold composting process will most likely not reach a high enough temperature during decomposition to kill off pathogens, so depending on what you've put in the pile, there may be some lingering harmful pathogenic bacteria, fungi, protozoa, worms, and other parasites as well as weed seeds in your finished product. A cold composting process is primarily anaerobic, meaning that your discards are broken down by microorganisms that thrive in an oxygen-deprived environment. In addition to being slower to break down, cold piles may be smellier or wetter than hot piles.

Hot composting is a faster, but more managed, compost process. This method requires attention to keep carbon and nitrogen in the optimum ratio to decompose organic waste. It also requires the right balance of air and water to attract the organisms that thrive in an oxygen-rich environment. Under ideal conditions, you could have the final compost product in four weeks to 12 months. If managed correctly, the high temperature of the pile will destroy most weeds, plant diseases, pesticides, and herbicides, plus any bug larvae or eggs.

How to Compost

Compost Ingredients

Organisms that decompose organic waste need four key elements to thrive: nitrogen, carbon, air, and water. Since all compostable materials contain carbon, with varying amounts of nitrogen, composting successfully is just a matter of using the right combination of materials to achieve the best ratio of carbon to nitrogen and maintaining the right amounts of air and water to yield the best results. The ideal carbon-to-nitrogen ratio for a compost pile is 25 to 30 parts carbon for every 1 part nitrogen. If your pile has too much carbon-rich material, it will be drier and take longer to break down. Too much nitrogen-rich material can end up creating a slimy, wet, and smelly compost pile. Fortunately, these problems are easily remedied by adding carbon-rich or nitrogen-rich material as needed.

"Greens" for Nitrogen

Nitrogen is one of the basic building blocks of life, and it is an essential element for growth and reproduction in both plants and animals. A higher nitrogen-to-carbon ratio is most commonly found in fresh organic material (often referred to as greens). Having plenty of greens in your compost pile makes sure the decomposers can grow and reproduce quickly. Some household greens you can add to your home compost pile are fresh grass clippings, food scraps, and coffee grounds.

"Browns" for Carbon

Another essential compound for all life forms is carbon, higher proportions of which can be found in brown plant material. Carbon acts as a food source for decomposers, helping to keep them alive while they break down waste. Typical browns you can add to a compost pile include dead leaves, branches, twigs, and paper.

To achieve the best carbon-to-nitrogen ratio in your home compost, a rule of thumb is to put in two to four parts brown materials for every one part green materials.

Oxygen and Water

Finally, like any other living organism, decomposers need oxygen and water to survive. To ensure a faster home composting process, you will need to make sure your compost system has the right amount of air and water. As mentioned above, if you are not in a rush for finished compost, you do not have to maintain your waste; the decomposition will still take place, just at a much slower pace. Optimal air flow can be achieved by layering materials, making sure your materials are in small pieces (ideally no thicker than a finger), and turning piles regularly (or adding another type of aeration system). As for water, the ideally moist household compost pile will be about as wet as a wrung-out sponge. If you are including food waste in your pile, it's likely it will be wet enough, but if not, just add water.

Temperature

Hot composting is achieved when the balance of greens, browns, air, and water creates ideal conditions for aerobic organisms to thrive. The optimal peak temperature for aerobic composting is 130 to 140 degrees Fahrenheit, which occurs when aerobic macro- and microorganisms are breaking down waste and reproducing at a fast rate. This high temperature also kills any lingering bacteria or weed seeds.

Consistent Aeration

Aeration encourages an aerobic environment, which helps to speed up the composting process and reduce odors. It is recommended you turn your pile (or rotate your tumbler) around once a week during summer and at minimum once every three to four weeks during winter. You can also add piping or large sticks to help increase natural airflow.

Maintaining Moisture

Moisture is essential for composting—your pile should always feel like a wrung-out sponge. Too dry a pile may cause the composting process to slow down. Too wet a pile may create an anaerobic environment, which can cause bad odors and also slow down decomposition. Water your pile (or add more wet materials) if it becomes too dry, and add carbon-heavy browns if it becomes too wet.

Size

A 3-foot cube is the ideal size for a compost bin or pile. You need a large volume of waste to be able to produce a high enough temperature for aerobic organisms to thrive. However, piles larger than 5 cubic feet are not likely to allow enough air to reach the decomposers at the center; they may also be harder to turn. Chop up larger pieces of food or yard scraps before adding to your bin or pile. The smaller the pieces, the quicker the decomposition process will be. A good rule is not to include anything thicker than a finger.

Location

The ideal compost location is a dry and shady spot. If you live in a rainy climate, avoid placing your pile or bin under eaves or places with poor drainage, or else the compost may get too soggy. If you live in a sunny environment, find a shady spot so it doesn't dry up too quickly and you don't have to keep adding water.

To start your pile, add alternating thin layers of greens and browns, ending with a layer of browns. (You can keep adding materials over time until you reach the optimal height of 3 feet.) Wet the compost pile if needed as you layer. Then leave the pile alone for four days to allow initial decomposition to begin, after which you can regularly aerate your pile or bin by turning with a pitchfork or garden fork and regularly monitor the moisture level.

Alamy

Compost Bin

Using a bin is the simplest and cheapest method for small-scale, at-home composting.

Closed Bin

A closed compost bin is an enclosed structure that keeps your composting materials together and helps to retain heat and moisture. Typically, closed bins have an open bottom and you place the bin directly on a patch of soil. The open bottom allows the nutrients in the developing compost to travel directly into the soil. You can either buy a compost bin or build one yourself, making sure to include a removable top so you can add more compostable materials as you accumulate them. Depending on the material you build your bin out of, you may have to drill or punch holes along the sides to allow airflow (or turn it manually for a hotter process). You should ensure that any holes or openings in the bin are small enough to prevent entry by rodents or any other animals of concern. You can build your bin to fit the amount of organics you expect to produce over time—size can range from 3 by 3 by 3 feet to a larger, three-bin system

You may already have some materials around the house to use for a DIY bin. Possibilities include:

- Wine crates
- Plastic storage bins
- Old wooden dresser drawers
- Garbage can
- Wire mesh
- Wood pallets

Open Bin

Open-topped bins (or open compost systems) typically require less maintenance and are better suited to composting yard waste (food waste may attract animals, and open bins are not animal proof). An open bin can be as simple as a loop of chicken wire that allows you to dump materials in. You can even just pile materials on the ground without an enclosure. With an open bin, you have easier access to the composting material. The primary disadvantage is that materials are loosely confined and may be easily accessed by animals or insects, or they may spill out over the boundaries of the bin or pile.

Open bins can be purchased, or you can make one yourself by driving metal stakes or wooden posts into the soil, ideally in a 3-by-3-foot square, and then wrapping the posts with wire mesh fencing. If you have the materials handy, you can also make an open bin from wooden pallets. You can use this method for either hot or cold composting, depending how much you'd like to monitor the balance of materials, turn the pile for aeration, and ensure the right moisture level.

Tumbler Bin

A tumbler is a sealed container that is mounted on an axle or base and can be rotated with a handle. By turning the container, you are aerating and mixing the waste inside, which will help foster aerobic conditions to break down the materials and speed up the composting process. A sealed drum tumbler retains moisture and heat (note that you may need to monitor moisture more carefully to ensure it doesn't get too wet). An aerated tumbler with built-in air vents, on the other hand, speeds up the composting process. With ideal conditions, tumblers can convert waste to finished compost in as little as three weeks, though a month or two is much more common. Compost tumblers can be purchased online or in most gardening stores.

Trench Composting

Another form of home composting involves burying your organic waste directly in the soil. Trench composting can help nearby plants develop water-conserving root systems. Moreover, it is odorless and invisible since all the waste is buried underground. Trench composting can be easier than maintaining a compost pile: All you have to do is dig a hole, fill it with organic waste, and cover it up with soil. Earthworms and other organisms in the soil do the rest of the work. You can trench compost any time of year as long as the soil in your yard remains pliable and manageable. However, this method is best suited to a single application of materials and is generally not practical if you want to compost materials on an ongoing basis, unless you have a lot of space and are willing to dig up your yard regularly.

One of the benefits of trenching is that it allows you to compost small amounts of cooked food waste, including meat, grains, and dairy, because animals and insects are less likely to be attracted to the material if it is buried deep underground. If you do decide to compost animal products, be sure to cover them with 12 to 18 inches of soil.

To start a simple compost pit, use a shovel to dig an elongated hole 12 to 24 inches deep. Fill in the pit with your organic waste, making sure the items are quite moist, and then fill the hole back up with soil. One of the downsides to this method, as with all cold composting methods, is that it takes longer for the waste to decompose. Trenching can produce finished compost in about 12 months, sometimes sooner if the conditions are ideal. Note that you will not be able to harvest the finished compost, so it is best to dig your trench wherever you'd like the nutrients to end up.

If you do not have much organic waste or enough space in your yard for a trench, you can also use the "dig and drop" method, which involves digging out small, 12- to 18-inch holes in the ground and burying the waste in them. You can dig and bury as you accumulate your waste and place small markers on top of the holes as you go so you don't dig in the same spot twice.

Tips for Trench Composting

- Don't dig near existing root systems so as not to harm or introduce bacteria to those plants.
- Don't plant anything directly on top of your trench as the soil will sink during the composting process.
- If you live in an arid area, water the soil on top of the trench to maintain moisture.

Matt Nager for NRDC

Vermicomposting

Vermicomposting, or worm composting, is a great indoor option if your outdoor space is limited (it can be done outdoors as well). You can do it year-round in a basement or garage or even under your sink. Vermicomposting produces natural, odorless castings, which are a nutrient-rich fertilizer, in about three to six months. There is very little maintenance required; the most significant time commitment is harvesting the vermicompost every few months.

You can purchase a cheap worm composter in stores or make one yourself. At its simplest, a vermicompost system can be a wooden or plastic bin with holes in the sides and bottom for ventilation and drainage (similar to a regular enclosed compost bin). A worm composter needs to be raised off the ground to allow excess liquids to flow out. A simple setup for worm composting is to place a taller plastic bin inside a shorter one. Then you have to add worm bedding and some soil. Bedding should be made out of carbon-heavy material to help hold the right amount of air and moisture for the worms. Some common materials for bedding are:

- Shredded paper
- Shredded cardboard
- Dry leaves
- Straw

Feed the worms once a week by burying your food waste under their bedding. Ideal food for the worms includes fruit and vegetable scraps, bread and grains, coffee grounds and used tea leaves. Don’t feed them any animal products or fats and oils, or anything too thick (like a watermelon rind or corncob). The moisture level of the bedding should be similar to that of a damp sponge, so make sure you check on that regularly as well.

The best types of worms to use for vermicomposting are red wigglers, a species that is very easy to maintain and actually prefers the compost environment over regular soil. Red wigglers can eat half their body weight in a day. A typical home system needs about a pound of worms. Check out this video to see how much one pound of worms looks like so you can ensure that you buy the right quantity for your bin.

Tips for Vermicomposting

Avoid using a metal bin as this can cause the inside to be uncomfortably hot or cold for the worms. Worms tend to thrive in temperatures ranging from 55 to 77 degrees Fahrenheit.

Keeping your worm bin indoors is ideal for many locations; you do not want your worms to freeze in the winter or get too warm in the summer.

Give the worms a day or two to adjust to their new environment and ease into the feeding to figure out the best amount of waste to give them. If you add too many food scraps, the worms may not be able to consume it all before the food rots and attracts insects.

Your worms should be fed about once per week. If you are going to be away from home for longer than that, remember to get a worm sitter so your worms don’t die.

What Can You Compost?

Anything that comes from the ground can be composted at home. While animal products can often be composted in municipal composting systems, at-home composting should avoid those items as they can attract animals and insects and leave pathogens in the final product.

WHAT YOU CAN AND CAN'T COMPOST IN YOUR BACKYARD

CAN BE COMPOSTED

- **Cardboard** (uncoated, small pieces)
- **Coffee grounds and filters**
- **Eggshells**
- **Fireplace ashes** (from natural wood only)
- **Fruits and vegetables**
- **Grass clippings**
- **Hair and fur**
- **Hay and straw**
- **Houseplants**
- **Leaves**
- **Newspaper** (shredded)
- **Nutshells**
- **Paper** (uncoated, small pieces)
- **Sawdust**
- **Tea bags**
- **Wood chips**
- **Yard trimmings**

SHOULD NOT BE COMPOSTED

- **Black walnut tree leaves or twigs** (release substances that might be harmful to plants)
- **Coal or charcoal ash** (might contain substances harmful to plants)
- **Dairy products and eggs*** (create odor problems and attract pests such as rodents and flies)
- **Diseased or insect-ridden plants** (diseases or insects might survive and be transferred to other plants)
- **Fats, grease, lard, oils*** (create odor problems and attract pests such as rodents and flies)
- **Meat or fish bones and scraps*** (create odor problems, attract pests such as rodents and flies, and might also carry pathogens)
- **Pet feces or litter*** (might contain parasites, bacteria, germs, pathogens, and viruses harmful to humans)
- **Yard trimmings treated with chemical pesticides** (might kill beneficial composting organisms)

*These materials should not be composted at home but may be accepted by your community curbside or drop-off composting program. Check with your local composting or recycling coordinator.

Source: U.S. Environmental Protection Agency, "Composting at Home," www2.epa.gov/recycle/composting-home.

From "Waste-Free Kitchen Handbook" by Dana Gunders

What Not to Compost

Pet Waste

Pet waste contains parasites and bacteria that can be harmful to humans and other animals if ingested. These pathogens can find their way into your body if you use compost that contains pet waste as fertilizer on edible crops. Compost must reach and remain at a minimum of 131 degrees Fahrenheit for three consecutive days to kill pathogens found in pet waste, and it is hard to regulate and monitor that if you are composting at home. It may be possible to compost dog waste in a home system, but you must follow USDA guidance carefully to ensure the proper conditions, and you should not include cat or any other pet waste. The USDA has resources that provide step-by-step instructions on how to compost dog waste, along with some recommendations to decrease health risks, including:

- Confining the compost pile to a specific area in your yard
- Not feeding dogs raw meat or fish and not including waste from unknown dogs
- Not applying dog waste compost to crops you intend to ingest
- Keeping children away from the compost pile

Inorganic Materials, Such as Plastic

Colored or Glossy Paper

Specialized color or glossy paper may contain toxic materials from the printing inks and additives that may be harmful to humans, animals, and plant life.

Diseased Plants

If your pile doesn’t reach a high enough temperature, plant diseases might survive and be spread to other plants when you use the compost.

Dairy and Other Animal Products

While animal products (meat, fish, eggs, bones, dairy, grease, fat) are organic, they can create odor problems and attract flies, rodents, and other pests to your pile or bin. These products can also carry pathogens that may survive the home composting process. You can trench compost small amounts of animal products.

These materials should be kept away from at-home compost collections. However, if you have a large amount of these materials, see if your municipality accepts food waste for composting, or reach out to a nearby composting program that may accept these items. Large-scale composting facilities can often take in these materials and compost them without the risks faced by a home composter.

More Tips for Composting at Home

Preventing or Getting Rid of Fruit Flies in Your Compost Bin

It is important to note that while fruit flies are annoying, they are harmless to humans and to compost. However, they reproduce quickly and can infest your yard or kitchen if not addressed. Here are some things you can do:

- Increase the carbon-rich browns in your compost pile to help the organic waste dry out. Fruit flies are primarily attracted to greens and will be less likely to linger if you dig a hole in your compost pile and bury greens under a layer of browns.
- Buy or make a fruit fly trap. (Note: Use these traps indoors only, as other critters can easily get trapped if you use them outside.)
- Boil your food waste before adding it to your pile to make it less enticing to fruit flies.
- Don't add new materials to your pile for a few days to force the fruit flies to go elsewhere for food.
- Purchase a compost keeper to collect food scraps in your kitchen, and add to your pile when it's full (or once a week or so). There are compost keepers that come with a charcoal filter to help absorb odors.

Safety Precautions

Take standard safety precautions when handling the waste (e.g., washing your hands afterward, avoiding touching your face). If you have a condition that predisposes you to an allergic reaction or infection, wear a dust mask while tending to your pile, especially in dry weather.

How to Use Compost

Compost needs to entirely stabilize and mature before it can be used. Not only can immature compost damage your plants, but it can also attract rodents and other pests to your yard. You will need to stop adding material in order for your pile to mature (although in no-turn systems, the bottom of the pile may provide finished compost even if the top of the pile is still active). You can identify finished compost by looking for these characteristics:

- Texture: Crumbly and smooth, without recognizable scraps.
- Smell: Like a forest on a rainy day, or rich earth. Traces of ammonia or sour odors means the compost needs more time to mature.
- Color: Dark and rich
- Size: One-third the original size of your pile
- Temperature: Within 10 degrees Fahrenheit of the temperature outside (especially in the middle of the pile)

Once you have confirmed that your compost is mature, here are some ways you can put it to use:

- Use it as mulch
- Add it to potting soil
- Work it into crop beds
- Distribute it on lawns

- Mix it into garden beds
- Feed it to potted plants
- Add it to soil around fruit trees

Compost cannot go bad, but it can get too wet, too dry, or too old. You can still use compost that is old; it just might not have as many nutrients in it as fresh compost.

Jim West / Alamy

Don’t Want to DIY? Outsource Your Composting

If you don’t want to compost yourself or can’t compost in your home, you can still collect organic waste and get it to a composter. Some cities have programs that provide curbside collection of organic waste along with regular trash on select days. Check your local municipal website or call 311 to see if your city has such a program. Or find a nearby community or municipal composting site where you can subscribe to a pickup service or drop off your organic waste. If your city doesn’t have a composting program, help jump-start interest by lobbying city council members, or start a community composting project yourself. If you outsource your composting, use a compost keeper to store food scraps between pickups or drop-offs. During summertime, you can also freeze your food scraps before taking them to your compost site to reduce the chance of foul odors or maggots.

Composting is not an exact science. It takes time and experience to figure out the best way for you to compost in your environment. Because it is a biological process, results may vary each time you try it, even if you don’t change your method at all. Don’t be afraid to tinker around with your bins, your ratio of browns to greens, or how often you aerate or water your pile. Remember—rot happens! Your compost pile will break down eventually no matter what. The more time you spend with it, the more you will learn.

Farmers lead composting revolution to heal African soils

Fernando Naves Sousa, *The Ecologist*

| 14th October 2014

Moussa Konate cultivating his fields. Photo: Fernando Naves Sousa.

The soils on which African farmers depend are getting poorer, writes Fernando Naves Sousa, depleted of nutrients and organic matter. This creates a huge challenge: to reverse the trend in an environmentally responsible way, while feeding a growing population. But it can be done - using organic composting techniques.

Moussa Konate has a secret. His fields of sorghum, millet and cotton are verdant and productive. Some neighbours are puzzled: they find it hard to believe he does not apply mineral fertilisers and other agro-chemicals.

"We have to feed the earth, so that it gives us what we need", says the farmer of Niamana, a village in southern Mali.

The humid heat of the rainy season makes everyone sweat. Attracted by some of the already mature sorghum grains, a few little red and yellow birds sing nearby. If one of the children throws a stone to scare them away, they escape and hide in the nearest trees.

Moussa uses his hand-made hoe to pluck weeds from his fields, adding them to the compost pile, under the big Baobab and next to the water well. That is where he works on his secret.

"I realized only good compost gives back the land what we take from it in a lasting way, and that is why I started producing it in great amounts."

Compost revolution

Moussa has learned how to produce good quality compost with the Malian organic cotton association, who came to the region five years ago.

Ever since, he has strictly followed the recommendations: to gather organic materials from his fields and kitchen waste, mix the available animal manure, weeds and crop residues and place the materials in layers, watering the pile in the dry season and turning it every two weeks for optimal decomposition. The result is a rich and crumbly black earth ready to nourish his nutrient hungry soils.

He participates in the Syprobio project *(see below)*, which investigates in a participatory way this and other innovations with small-scale farmers, who represent between 70% and 80% of the local population.

Altogether, 100 farmers from Mali, Burkina Faso and Benin participate in this large on-field research, some focusing on how to increase their most precious asset: soil fertility.

Bringing science and farming together

In Moussa's trial, he carefully quantifies and compares the advantages of applying good quality compost, comparing with the traditional habit of spreading undecomposed organic matter in the fields. The results confirm the expectation:

"The cotton parcel where the quality compost was applied has much taller plants and more cotton buds when compared to the parcel where undecomposed organic waste was applied, as we used to do."

Moussa stopped using the mineral fertilisers before learning how to produce the good compost: *"The chemical fertilisers only help the crops in the first year, while the effect of compost can be felt up to three or four years after applying it."*

And compost represents a more durable investment, he emphasises. *"Besides, if it rains after applying mineral fertilisers, they will be washed by the water, whereas compost absorbs water instead of being carried by it, further helping the crops."*

When it rains, the muddy runoff builds up behind the cordons. Over time they grow to form effective and rapidly vegetating catchment barriers, reducing erosion and helping rainwater to infiltrate into the soil.

The other obvious advantage is the economic cost: making compost does mean work - but it costs no money, something of huge importance in a cash-poor society.

'Our food comes from the land we walk on'

Farmers like Moussa know they cannot afford to ignore the quality and fertility of the soil underneath their feet: *"It does not matter if you live in the countryside or in the city, we cannot forget that everything we eat comes from the land we walk on. The way we treat it will determine our future."*

According to the United Nations Food and Agriculture Organisation (FAO), soil degradation and soil fertility loss in Africa have risen in the last few decades. This trend is above all related to decades of inappropriate farming practices, deforestation, desertification, overgrazing and intensive soil erosion.

Over the last 30 years, food production in the continent remained more or less stable, despite a significant rise in cultivated surface. During the same period, however, the continent's population has more than doubled.

To feed a growing population by increasing food production in a sustainable way will probably be Africa's greatest challenge during this century.

'Holding' the good earth

Besides returning nutrients to the soil, as Moussa and other farmers are already doing, it is also important to keep the fertile top layers of soil from disappearing.

After decades of deforestation and aggressive agricultural techniques, soils are exposed to erosion. If vegetation is removed and fields are ploughed, torrential rainfall will have a clear road to carry away the top layers of the earth - where soil fertility concentrates.

To prevent water from washing away their livelihood, many farmers in the region started building '*cordons pierreux*', or stone lines. The technique is simple: stones of different sizes are piled in long lines along contours on hillsides subject to rapid water runoff and erosion.

Then when it rains, the muddy runoff builds up behind the cordons. Over time they grow to form effective and rapidly vegetating catchment barriers, reducing erosion and helping rainwater to infiltrate into the soil.

Oh rose thou art sick ...

The links between soil fertility and food security can at times be less obvious. A poorer soil is a headache for farmers, not only due to weaker yields, but also because of an otherwise harmless looking plant: a little pink flower called *striga*.

Despite its beauty, *striga* is a feared parasite which stifles cereals, especially sorghum. The unusual feature of *striga* is that it likes poor soils, therefore having become even more infestive in the nutrient poor soils of Western Africa.

Koro Diarra, from the small village of Kombre, in southern Mali, is one of the farmers who declared war on the little pink flower. Her strategy is to increase her field's fertility by applying compost, which has the double advantage of controlling *striga* and nourishing her crops, increasing yields.

"Sorghum is the base of our diet, it's very important to us, and that's why we cannot ignore striga", says Koro.

In Moussa's fields, *striga* is already rare, as the soil has become too rich for it to thrive. The farmer is seen by local technicians and other farmers as a model producer. *"I invested a lot of effort in compost production. With the good results, I was motivated to increase the amount"*, he says.

Other farmers visit his field to learn from him. *"Some neighbours come to see my fields and understand that the effort of producing compost is worth it. After all, it is the ground that feeds us".*

***Fernando Naves Sousa** is a conservation biologist and researcher at FiBL - The Organic Farming Research Institute, in Switzerland. He also contributes to different magazines as a freelance journalist.*

Syprobio - Systèmes de Production Biologiques - is a participatory action-research program developed by FiBL (Organic Farming Research Center) in partnership with farmer associations and research institutions in Mali, Burkina Faso, and Benin, representing a total of 10,000 farmers.

The project is financed by EuropeAid and has a period of 5 years, having started in 2011. Syprobio aims to empower local farmers in the process of investigating and developing organic farming innovations which can promote food security and sovereignty, as well as a better farm income, particularly through the improvement of soil fertility, pest management and adaptation to climate change.

05. Combustion with Energy Recovery (Waste to Energy)

Current Environmental Issue Study Resources

Key Topic 5: Combustion with Energy Recovery (Waste-to-Energy)

1. Identify examples of closed loop energy systems and facilities.
2. Compare method of carbon sequestration and describe their potential as an energy source.

Study Resources

Closing the loop: integrative systems management of waste in food, energy, and water systems – *Davis et al., 2016*

Carbon Sequestration – *UC Davis, 2021*

Closing the Loop: Waste-to-Energy Trends- *Larry Burton, Temarry, 2021*

Waste-to-Energy Where it is Needed the Most – *United Nations, 2018*

G7 countries eye waste-to-energy incineration as part of plastic pollution solution- *Emily Chung; CBC News; 2018*

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Closing the loop: integrative systems management of waste in food, energy, and water systems

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Abstract Modern food, energy, and water (FEW) systems are the product of technologies, techniques, and policies developed to address the needs of a given sector (e.g., energy or agriculture). Wastes from each sector are typically managed separately, and the production systems underlying FEW have traditionally treated pollution and waste as externalities simply diffused into the ambient environment. Integrative management that optimizes resource use presents opportunities for improving the efficiency of FEW systems. This paper explains how FEW systems can be optimized to (1) repurpose or cycle waste products, (2) internalize traditional externalities, and (3) integrate wastes with resource inputs across systems by diverting waste by-products from one system to meet demands of another. It identifies the means for "closing the loop" in production systems. Examples include management of legacy wastes from fossil fuel industries (coal and natural gas) and integrative designs for advanced renewable systems (biogas from waste, bioenergy from CAM plants, and solar). It concludes with a discussion of how studying the governance of such systems can assist in tackling interconnected problems present in FEW systems. New governance arrangements are needed to develop solutions that can align with regulatory frameworks, economics incentive, and policies. Four aspects of governances (property rights, policy design, financing, and scale) emerge as tools to facilitate improved institutional design that stimulates integrative management, technology innovation and deployment, and community development. The conclusion offers a framework through which integrative management of FEW systems can be linked to value chains in closed-loop systems.

Keywords Closed-loop production systems · Integrated systems analysis · Bioenergy · Biogas · Hydraulic fracturing · Acid mine drainage · Irrigation · Water consumption · Public policy · Governance

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Introduction

Many modern societal challenges stem from systems inefficiencies that waste resources. These inefficiencies are myriad and fundamental. Of the 103 exajoules (1 exajoule $= 2.78 \times 10^{11}$ kWh) of energy consumed in the USA annually, only 73 % are delivered to an end use, reflecting 27 % waste (EIA 2011). In the case of food systems, an average of 33 % of grain, vegetables, red meat, and poultry are wasted annually (Buzby et al. 2011; Giovannucci et al. 2012). Irrigation of crops that support food production consumes 135 million m^3 of water, amounting to 77 % of all water consumption in the USA, even though only 6–14 % of agriculture is irrigated in this country (USDA 2007, 2012). Improving efficiencies of the systems that supply food, energy, and water (FEW) requires major infrastructure overhaul and substantial financial investment. Near-term solutions for co-managing FEW systems more efficiently provide critical steps during a more fundamental transition to policy, economics, and infrastructure that closes the loop on waste. This article describes strategies that view wastes from FEW production as opportunities for enhancing overall efficiency if systems are managed with an integrative perspective and provides a framework for evaluating how systems might be more tightly integrated.

Energy systems in the USA are still predominantly fueled by fossil resources, with waste products that impact air, land, and water quality. Major air pollutants from the coal industry include mercury, sulfur oxides, and nitrogen oxides, among others. Water pollutants include metals such as iron and aluminum, and sulfur that leads to acid mine drainage. Prior to the establishment of the Clean Air Act of 1970, Clean Water Act in 1972, and the Surface Mine Control and Reclamation Act of 1977, these pollutants were generally unregulated and assumed to be diluted and discarded upon discharge. Despite increased regulation and quality standards since the 1970s, the pollution from historic activity persists in the environment along with newly generated waste from modern fossil fuel extraction technologies. Horizontal drilling and hydraulic fracturing for natural gas production is a recent technological advance for the fossil fuel industry, but is the source of new methane emissions, has a high water demand, and generates a new form of waste water to be regulated.

Alternative energy systems are growing as a means to offset the impacts of fossil fuel systems. Yet systems that use renewable resources generate waste as well. The manufacturing processes associated with solar, wind, hydrogen, biomass, and hydroelectricity all consume resources and generate waste even if at a lower level than fossil fuel technologies (Pehnt 2006; Varun et al. 2009). For example, large-scale solar energy deployed in arid regions requires substantial water for cleaning to maintain efficient energy generation (Ravi et al. 2014). Some renewable energy systems, however, use waste as the feedstock for energy generation, demonstrating the potential for improving systems efficiencies by integrative management. Municipal solid waste management is an industry unto itself, but integrating energy and waste management creates opportunities for reducing life-cycle impacts of otherwise separate production processes (Cherubini et al. 2009; Münster and Lund 2009). It is estimated that animal manure alone, the largest waste resource that is uniform in format, could generate between 9 and 25 exajoule (EJ) (Hoogwijk 2003), or 7 % of global energy consumption (IEA 2013).

The US food system depends heavily on international trade despite the large agricultural land resource available domestically. Agricultural production in the USA is dominated by corn (*Zea mays*) crops, with the majority of corn grain used for livestock feed and bioethanol. There are 35 million ha (86 million acres) allocated to this one crop in the USA with only ~8 % used for human food (FAOSTAT 2015). In the USA, there has been a decline in farmland since the middle of the twentieth century as crop diversity decreased and farming in some regions was abandoned (USDA 2012). Yet, the American diet has become more diversified over the same time period through the increase of imported food commodities. With ca. 33 % of food resources wasted (Giovannucci et al. 2012), there are clear opportunities for improving the efficiency of the food economy. An alternative to reducing waste is to utilize it for other purposes. Both abandoned agricultural land and wastes can be used for bioenergy feedstocks (Campbell et al. 2013; Davis et al. 2014). Agricultural lands can also be diversified to enhance nutrition, ecosystem services, and efficiency within food supply chains (Giovannucci et al. 2012).

Food and energy systems impact water in many ways. Agriculture is the leading consumer of water. Even in the USA, where only 6 % of farmland is irrigated in an average year (USDA 2007), and 14 % in a recent drought year (USDA 2012), irrigation accounts for an average of 77 % of water consumption (Kenny et al. 2009; Scown et al. 2011). Consumption of water for irrigation is of growing concern due to risk of increased drought expected in some regions as climate change progresses, and opportunities for reducing or reusing water would greatly benefit this production system. Water resources are also affected by withdrawals that result in a change to water quality. In this case, water is not technically consumed, but is altered before being returned to the source drainage basin. Depending on the change in quality, there can be substantial chemical and biological consequences for this change. The vector of change (e.g., heat, chemical load) is a waste from the industrial system that uses withdrawn water.

The structure of economic incentives in FEW systems has led to wastes being treated as externalities. However in some cases of both current and legacy system wastes, these byproducts may offer value-added opportunities for both improving efficiency of production and reducing environmental impacts. Systems that are designed to incorporate waste back into one or more stages of production are known as "closed-loop systems." Closed-loop systems improve the sustainability of manufacturing a product by focusing on the entire lifecycle from the extraction of raw material to disposal. It focuses on recapturing and reusing material within a process, across processes, or across different products, and the use of biodegradable/bio-compostable materials to reduce the environmental impact of production and consumption (Dekker et al. 2013; Ellen MacArthur Foundation and McKinsey & Company 2014; Winkler 2011). In the text that follows, we provide four examples of how integrated FEW systems can be designed as closed-loop production systems where waste is repurposed and utilized for multiple values along and across different production cycles. We then describe the potential for successful integrated systems management with governance that carefully addresses property right institutions, policy design, long-term financing, and scaling issues.

Example 1: coal mining waste repurposed as useful chemicals

Coal mining creates a large waste stream including tailings and, in some cases, acid mine drainage (AMD). AMD is formed through oxidative weathering of sulfide minerals exposed during the mining process and is a metalliferous, acidic waste stream. Once exposed, many underground mines continue to discharge decades after mining ceased. Reclamation efforts can treat AMD, but do not eliminate it, and create large public costs expended toward maintaining water quality. There is potential for material reuse and resource recovery to reduce the ongoing waste stream created by mining.

Reuse or processing of AMD has been investigated for three key uses: metal recovery, phosphorous removal from municipal wastewater, and hydraulic fracturing source water (Fig. 1). Each has the potential to increase the sustainability of mining and reduce the impact of AMD if the processes are made more efficient. Hedin (2006) showed that a saleable product can be extracted from AMD; the author extracts iron oxy-hydroxide sediments from treatment systems for abandoned coal mines to sell as pigment for paints and even crayons (Hedin 2006). Various extraction methods have been suggested including biochemical methods (Sahinkaya et al 2009), sequential precipitation (Matlock et al 2002; Wei et al 2005), and titration (Jenke and Diebold 1983), although few of these processes have been widely adopted. AMD is a diffuse pollutant, so a decentralized, low cost, potentially portable approach could lead to increased revenue potential and increased adoption by the industry.

The iron compounds present in AMD are known to be effective sorbents for phosphate (e.g., Dobbie et al. 2009), so much so that phosphorous availability has been identified as a potential limitation to recovery of AMD impacted waterways (e.g., DeNicola and Lellock 2015). Wei et al. (2008) and Dobbie et al. (2009) show effective phosphorous removal using iron precipitates from AMD when applied as tertiary treatment of municipal wastewater, and these results are consistent with studies describing co-treatment of AMD and municipal wastewater (e.g., Strosnider and Nairn 2010). While there is widespread potential application for phosphorous control using AMD, the proximity of either major agricultural pollution or municipal wastewater to iron-rich AMD limits widespread application of the technology.

AMD has also been explored as source water for hydraulic fracturing (Macy et al. 2015). Since hydraulic fracturing requires a large amount of water, the Pennsylvania Department of Environmental Protection has suggested use of AMD rather than freshwater as source water (PDEP 2013), and other states are following this example. Drawbacks such as trucking distances, potential for well bore scaling due to high iron concentrations, and reactions with sulfate in the AMD to form insoluble barite or toxic hydrogen sulfide gas could limit reuse of AMD for hydraulic fracturing. Efficient, low cost treatment to remove key constituents and effective planning to reduce trucking distance could allow for this reduction in waste. Integrative management of AMD and source water for hydraulic fracturing has the potential to reduce both water withdrawals and new waste in regions that still struggle to contain legacy waste from mining.

Other pathways for reusing AMD are reviewed by Kruse and Strosnider (2015), and include iron seeding in the ocean (Hedin and Hedin 2015) and sequential flooding of mine pits to maximize CO_2 sequestration (Younger and Mayes 2015). Each of these pathways is associated with other consequences that are controversial and would need to be weighed carefully against the benefits for waste remediation.

Fig. 1 Conceptual diagram of waste from coal mining (acid mine drainage) repurposed to meet resource demands within the energy industry (injection water for hydraulic fracturing) and resource demands for other markets (pigment and phosphorous remediation). Image for phosphorus remediation used with permission from Kate Heal, University of Edinburgh (www.geos.ed.ac.uk/research/cecs/water.html)

Example 2: hydraulic fracturing flowback and produced water reuse and treatment

Horizontal drilling and hydraulic fracturing are used together to extract gas, gas condensates, and oil from hydrocarbon-rich shale formations deep underground. The process requires a large volume of water (about 5 million gallons per well) that is mixed with various chemicals and produces significant quantities of wastewater (25–50 % of the injected fluid). The fluid that is injected is a mixture of water (~85 %), crystalline silica used as a proppant (~14.5 %), and chemicals (~0.5 %) including hydrochloric acid, glycols, methanol, ammonium chloride, petroleum distillates, and a number of organic chemicals that act as inhibitors and bactericides (e.g., fracfocusdata.org). The initial composition varies by producer; some states require disclosure of the fluid chemistry on the web repository, fracfocus.org, although details about some constituents are withheld due to their proprietary nature. The water that returns to the surface is termed produced water; it is “produced” when the pressure is released from the well bore, allowing the fluid to return to the surface. Management solutions for this wastewater are still needed.

The wastewater that returns within the first 10 days is called “flowback” water. The flowback portion of the produced water tends to have a composition more similar to the injected fluid than the later produced water, and makes up approximately 15 % of the produced water (Mantell 2011), depending on the shale play geology. The remaining produced water returns to the surface throughout the life of the well. Barbot et al. (2013) analyzed several hundred produced water samples; they found that “Flowback water is dominated by Cl-Na-Ca with elevated bromide, magnesium, barium, and strontium content,” while over time, the produced water will be more representative of the shale formation brine, potentially including elevated chloride, bromide, sodium, calcium, barium, strontium, and radium. This large waste stream, comprised of flowback and produced water, must be managed and is typically treated for reuse through filtration and minimal removal of dissolved salts, treated for discharge using industrial wastewater treatment methods that ought to remove contaminants to meet discharge permit requirements, or disposed of in a Class II Injection Well.

Class II Injection Wells are wells used for injection of liquid waste from oil and gas operations as defined in the Safe Drinking Water Act. In the Marcellus and Utica Shale region of PA, WV, and OH, the Injection Well infrastructure is available mostly in Ohio, so produced water is trucked long distances for disposal (Mantell 2011; Lutz et al 2013; Rodriguez and Soeder 2015). Injection wells have potential problems including induced earthquakes and wastewater migration following the path of undocumented abandoned wells (Justinic et al 2013; Keranen et al 2013; Kim 2013; Rodriguez and Soeder 2015). An alternative pathway for the chemicals in produced water is needed to reduce cost and environmental impacts of hydraulic fracturing.

The clearest application of produced water reuse is for source water for further hydraulic fracturing. This is often the fate of the “flowback” portion of produced water. There are several chemical limitations to this, but Mantell (2011) reports high potential for produced water reuse. High total dissolved solids will dictate the mixing ratios between freshwater and wastewater, while high total suspended solids must be filtered out in order to reduce friction. Sulfate can drive precipitation of barite, scaling a future well, or be metabolized by sulfate-reducing bacteria to create toxic hydrogen sulfide gas (e.g., Mantell 2011; Murali Mohan 2013; Macy et al 2015). Trucking and storage are other limitations that companies must overcome for direct reuse of produced water for hydraulic fracturing.

Beyond direct reuse, there have been failed attempts at land application of produced water that led to soil degradation and vegetation damage including a test application to 0.2 hectares of Fernow Experimental Forest in West Virginia in 2008 (Adams 2011). Land application in Fernow Experimental Forest led to death of over half of the trees in the test plot within 2 years, soil had elevated sodium and chloride concentrations that decreased over time and the author suggests that the application may have impacted organic matter cycling (Adams 2011). Some jurisdictions, including parts of Ohio, Pennsylvania, and New York, also allow use of oil and gas brine for road deicing, although this practice varies widely from place to place (e.g., Schlanger 2015). Typically, no pretreatment is required; however, regulations require a certain distance between an application site and waterways in recognition of the potential for migration of contaminants into water bodies through runoff (Schlanger 2015).

Treatment of produced water is a challenging field due to the high concentrations of total dissolved solids and the complex chemistry of the fluid; fluid composition varies spatially (Barbot et al 2013) due both to the initial composition of the hydraulic fracturing fluid and local geologic conditions. Desalination (Shaffer et al 2013), membrane technologies, and thermal technologies (Rodriguez and Soeder 2015) are all suggested treatment methods for produced water. Unpublished research conducted at Ohio University aims to sequentially treat produced water to extract saleable products from the waste stream (personal communication, Dr. Jason Trembly). This is a new and growing area of research to find reliable, low cost treatment technologies that are competitive with the cost of underground injection. Integrative management of hydraulic fracturing waste with water management and other system resource demands could be a step towards more environmentally sustainable energy.

Example 3: anaerobic digestion as an opportunity for integrating waste management across food, energy, and agricultural systems

Energy generation from diversified waste streams has many benefits relative to corn, the primary biofuel in the USA today. If bioenergy feedstock were instead sourced from wastes, there would be (1) savings in both land and energy requirements (for manufacturing fertilizer, cultivation, and harvesting), (2) reduced greenhouse gas emissions from soil disturbance, and (3) reduced costs of waste disposal. It is estimated that 254 million tons of municipal solid waste are generated in the USA annually, with only 34 % recycled into other products (EPA 2015). The cost of disposal is $50 per ton, amounting to a national cost of 8.4 billion dollars spent annually on disposal of 168 million tons of food, agricultural, and landscaping wastes (EPA 2015). These wastes could instead serve as feedstocks for anaerobic digestion (AD) to generate methane fuel (gas or liquid) identical to the natural gas that is extracted from underground deposits and consumed at a rate of 29 terajoules annually in the USA (EIA 2015).

The production of methane biogas using AD is not new technology, but has only recently been developed commercially in the USA following successful examples that have emerged throughout the world in the last few decades (Aslanzadeh et al. 2014; Mata-Alvarez et al. 2000). Traditional AD efforts are focused on processing human and animal biosolids and municipal wastewaters, but there is a growing body of literature on AD of food and plant-based waste products (Kiran et al. 2014; Mata-Alvarez et al. 2011; Zhang et al. 2007; Zhang et al. 2014). The establishment of dry AD as an alternative to slurry-based wet AD has also helped advance the potential of food and other solid waste materials as desirable substrates for biogas generation (Brown and Li 2013; Michele et al. 2015).

Codigestion, AD with mixed materials instead one uniform feedstock, is also gaining increased scientific attention because sorting and processing of raw waste materials is a major limitation for system sustainability and there is mounting evidence for increased biomethane potential during codigestion (Mata-Alvarez et al. 2011; Siddiqui et al. 2014). Optimizing complex codigestion remains a challenge because the highly variable feedstock encountered in practice at the commercial scale forgoes the possibility of using one set of precise conditions. Nevertheless, there are examples of commercial AD that use multiple waste streams simultaneously. With continued research in this area, there is tremendous potential for energy generation from waste.

By-products of AD can be used for fertilizer. Unlike other pathways for converting waste to fertilizer, like livestock waste (manure) applied to crops as organic fertilizer or composted food wastes used as soil amendments, the AD system produces energy as primary product. Another example of wastes from a bioenergy production system that is used for fertilizer is the nutrient-rich by-products of fermentation in sugarcane biorefineries that are recycled backed to fields where the crops are grown. Similarly to this example, effluent from AD is used to fertilize plants cultivated as feedstocks or for other purposes. The effluent can also be applied to field crops to replace the need for conventional fertilizers that are manufactured at a high energy cost.

Prototype systems are being tested for the efficacy of managing anaerobic digestion and hydroponic vegetable production in the same greenhouse, for example at Ohio University (Fig. 2). This system is developed as an off-grid greenhouse that is passively heated by solar energy and the heat from the digester. Rainwater collected on the roof of the greenhouse is used in the hydroponic system and to make the slurry in the anaerobic digestion system. Effluent from the digester is diluted and then added to the hydroponic solution as a fertilizer. This is perhaps the best example reviewed here of a closed-loop system that includes food, energy, and water: Energy in the form of biogas and heat is produced from waste, the by-product of this energy production is used as fertilizer to grow food, the structure that houses the energy and food production collects water that cycles through both the energy and food production systems, and the waste from the food production can be returned to the digester as a feedstock. The project at Ohio University aims to determine the scale that would be required for these systems to be completed closed-loop.

Developing the infrastructure for AD systems requires investment, but when considered in the context of savings that can be made in other sectors (agricultural and waste management), this investment can be offset by both environmental and economic returns. Management that considers waste,

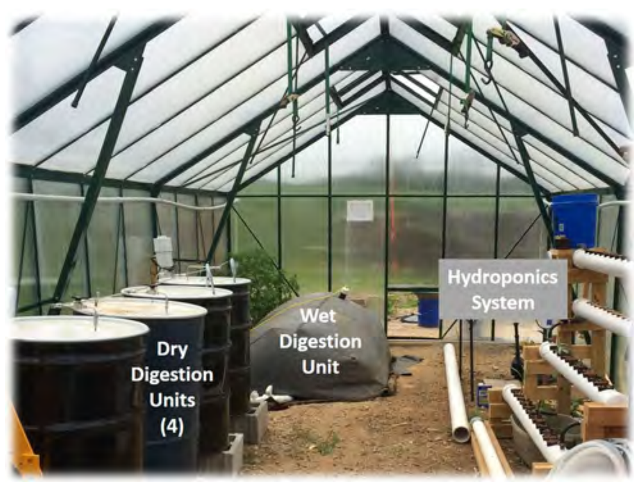

Fig. 2 Inside view of pilot-scale AD research at Ohio University where digestion units and a hydroponics system are managed together in a glasshouse enclosure to purposefully capture the wastes from one system to be used for the other. Water for both systems is obtained through a rainwater collection system (not pictured) installed on the glasshouse

energy, and agriculture under one umbrella can improve efficiency and increase environmental benefits, moving systems that are currently costly and wasteful to a more closed-loop condition.

Example 4: reduced water consumption through integrated management of renewable energy in arid regions

The focus of advanced bioenergy development goals has moved away from lands that are used for food crops or native ecosystems, and more toward degraded, abandoned, and marginal lands (e.g., Somerville et al. 2010; Campbell et al. 2013). In these conditions, that are usually less ideal for agriculture, greater inputs are required unless crop species with traits specifically suited to the environment can be identified. In arid conditions, plants that use crassulacean acid metabolism (CAM) are adapted to thrive with very low water inputs. In the USA, where 77 % of water consumption is used to irrigate 6–14 % of cropland, mostly in drier climates, there are substantial benefits to exploiting CAM species in agricultural production instead of conventional crop species (Borland et al. 2009; Davis et al. 2011, 2014, 2015; Cushman et al. 2015).

Plants with CAM photosynthesis are increasingly recognized as potential crop species that can thrive in abandoned dry land agriculture because they take up carbon dioxide through stomata at night instead of during the day (e.g., Davis et al. 2014). The cooler nighttime temperatures allow reduced water loss from the plants relative to the water lost through evapotranspiration if stomata opened during the day, as most crop species do because of their reliance on C_3 or C_4 photosynthetic pathways. Reduced water loss leads to a lower water demand. With small amounts of irrigation, CAM species like those in the *Agave* genus can yield as much as other commercial crops that receive anywhere from two to ten times the water inputs (Davis et al. 2014, 2016). Given the amount of water used in agriculture in the arid USA, and the clear difference between common commodity crops and potential CAM crops, irrigation is wasting water that might otherwise be used for other purposes.

Arid regions are often also targeted for solar development because the low level of cloud cover maximizes the radiation available for conversion to electrochemical or heat energy, either through photovoltaics or thermal solar power plants. While these systems are efficient renewable energy generators with much lower greenhouse gas emissions than fossil fuel energy systems, there is substantial water required to clean dust from the solar panels and maintain optimum power production (Ravi et al. 2014). It has recently been calculated however that the co-management of solar panels and CAM crops for bioenergy could improve the efficiency of energy generated (Ravi et al. 2014). By using the waste water from washing the solar panels to irrigate (in small quantities) CAM plants grown side-by-side with the panels, both solar energy and biomass energy production are optimized (Ravi et al. 2014; Cushman et al. 2015).

Advanced bioenergy systems require careful consideration of land resources, competing land uses, ecological suitability, and crop tolerance to climate change. The need for renewable energy sources that reduce greenhouse gas must be weighed against the resource demands required for renewable energy production. An integrative management perspective would allow resources wasted by one system to be used to meet the demands of another, in effect closing the loop on waste. Resource inputs for agricultural systems that support bioenergy vary depending on the crop species and location where the crop is grown. The example of integrative management reviewed here works in arid ecosystems, but there are parallel opportunities for integrative management of agriculture and energy in any region.

Governance of integrated FEW systems: challenges and opportunities

The diverse examples provided above demonstrate how pollution and waste can be reduced by treating them as productive inputs, and eliminating needless inefficiencies with more inclusive technical and integrated approaches. The ability to realize these gains will however challenge current governance arrangements for FEW systems to achieve tighter feedback between waste and inputs, even though significant opportunities exist for improved system design. A recent study by the MacArthur Foundation and McKinsey (2014) suggests there is an estimated \$4.5 trillion to gain in economic growth from altering the current structure where by-products are treated as waste to a closed-loop system in which materials are reincorporated into production processes. Understanding how current FEW systems have evolved to miss these opportunities and how redesign can close waste systems will require examining the governance arrangements which have incentivized current production, distribution, and waste management systems.

Governance as a field of study looks at how the institutional structures of public and private economies influence outcomes. It includes a broad array of social and natural sciences that examine how social coordination is achieved to produce and implement collectively binding rules and provide public goods (Risse 2011). Governance systems are composed of institutions, defined as the collection of both formal and informal rules used for determining inclusion in decision making, what actions can be taken, the consequences of these actions, and how individual actions are aggregated into collective decisions (Kiser and Ostrom 1982; Ostrom 1990). Institutions are what structure incentives and risk, the distribution of the benefits and costs of actions, and largely influence the sustainability of natural resource systems (Hanna et al. 1996; Ostrom 2008).[1] We highlight four critical aspects of the governance arrangements around FEW systems that are challenges to integration: property right institutions, policy design, long-term financing, and scale.

1. Property right institutions and resources

Central to any resource allocation system are property right institutions (Bromley 1991). Property rights determine the flow of both rights and benefits, as well as responsibilities and costs from the use of a resource. They are particularly important in the study of integrated FEW systems as they govern what is considered an economically useful component of a resource and what is considered waste. For example, property rights to mineral resources are associated with land rights which historically have led to the benefits from mineral extraction out-valuing the damage to land and water resources. Regulatory policies have now placed an additional cost and responsibility on mineral extraction in an attempt to internalize the costs of associated environmental damages; however, these regulatory costs occurred too late to deal with historic impacts, and while the rights to the economic benefits went to private owners, the responsibilities for the negative impacts were allocated to the public in terms of environmental clean-up.

Creating systems that better align rights with responsibilities and create incentives to recycle and reuse waste streams will require new property rights structures. Emerging initiatives toward closed-loop systems such as cradle-to-cradle production have created value in the waste stream as manufacturers (1) design materials that can be reused as raw material and (2) purchase end-of-life products from consumers via upfront contracts and rebate programs (Braungart and McDonough 2002; McDonough and Braungart 2013). Contractual arrangements with consumers for material that will be incorporated back into production has effectively allocated a new property right to the waste stream as raw material, and incentivized the allocation of material for reuse and recycling directly to the manufacturer through rebate agreements.

2. Policy design for closed-loop systems

Designing effective policy instruments to incentivize and facilitate closed-loop FEW systems will entail subtle changes to property rights and the associated responsibilities. Traditionally, the policy instrument used for internalizing externalities into production decisions has been regulations, which allocate a responsibility to minimize or prevent negative externalities in using natural resources by imposing a cost (Bromley and Paavola 2002). However, these first generation policy instruments have been critiqued as not providing a reason to go beyond mere compliance, not providing significant flexibility toward improved economic efficiency, and not generating incentive to develop new technologies, or in terms related to this discussion, create new integrative closed-loop production systems (Susskind et al. 2001; Kraft and Vig 2006). Research suggests that flexibility of market-based policy instruments are favorable over that of regulatory policies for (1) stimulating the innovation of new technologies, (2) incentivizing environmental behavior beyond mere compliance, and (3) reducing the economic inefficiencies associated with regulations (Gunningham et al. 1998; Stavins 2003).

If closed-loop production is to be successful, the next generation of environmental policy instruments will need to be designed to not only mimic markets as do cap-and-trade policies, but rather to directly stimulate new resource allocation systems that create value in what are today regarded as wastes. Policy design will need to generate new systems for reducing environmental and economic inefficiencies in production systems and reframe waste as a valued resource rather than a cost in production. An example of such a program is the recent "feebate" program introduced in California in 2008 where high emissions vehicles are charged an additional fee that is used as a direct rebate for purchases of low emissions vehicles (Bunch et al. 2011). The emission waste is utilized as a disincentive for the purchase of high emissions vehicles and simultaneously provides a subsidy for the purchase of low/zero emissions vehicles. Similar programs have been proposed for landfill and waste management (Puig-Ventosa 2004).

3. Financing long-term investments

Many of the policy interventions needed to produce more efficient and effective closed-loop waste systems and tightly integrated FEW management will have to be directed at better aligning private and public interests in capital markets. Financial instruments are needed to invest and redesign infrastructure that allows integration across systems. The haphazard development of water, waste management, food system, energy production, and distribution infrastructures, including associated infrastructure for transportation and utilities, has not taken into consideration potential complementarity. Whereas waste disposal has traditionally been designed to move waste out of urban areas, integration into food and energy production will require new infrastructure investment options. For example, biogas production facilities that can utilize waste require site integration into regional plans, connection to energy supply grids, and locations on transportation

[1] Alternative approaches within the broad field of governance studies do exist, across the theoretical spectrum. This paper uses that within the positivist political economy tradition in order to focus on incentives that structure the reduction of negative economic externalities.

networks that can allow access to waste products (e.g., sewage facilities, food water, agricultural and landscape waste) rather than being isolated from the locations where wastes are produced and situated far from energy production and demand.

Existing capital markets are poorly suited for funding infrastructure and projects that can improve long-term resource efficiencies but that cannot be translated into short-term economic efficiency, increased revenue, or reduced risk (Labatt and White 2003). For example, bonds are associated with the jurisdictional entities that offer the backing to secure investment risk (municipalities, states, nations) and provide a poor fit to resource systems that cross jurisdictional divisions at a regional and even international level. The Water Infrastructure Finance and Innovation Act (WIFIA), a major source of funding for water infrastructure in the USA, has heavy federal oversight and is considered too inflexible for meeting the needs of green infrastructure and closed-loop financing. Green bonds, a relatively new financial tool, have been critiqued as being poorly linked to environmental outcomes and more about branding than actual impact (The Economist 2014). A new generation of financial instruments will be needed to improve infrastructure and promote projects that gain value from integration, instead of funding separate independent initiatives.

The risk burden for investments in FEW has a number of characteristics particular to the integrative nature of the desired systems. Financial instruments and incentives will need to take into account (1) how risk is managed by agricultural producers, (2) investors in the infrastructures needed to process and move waste materials, and (3) the incentives facing investors in both small-scale projects and large regional infrastructure. The importance of understanding risk is ubiquitous. For example, corn has emerged as the dominant biofuel crop due to the existence of multiple markets for the product and the ability of a farmer to use this as a hedge against risk in commodity price changes for any single market. Depending on demand, it can be sold for animal feed or as biofuel feedstock, as well as qualifying for federal farm subsidy programs (Demirbas 2008; Hochman et al. 2008).

Similarly, many production activities occur within a larger supply chain of multiple producers and suppliers interacting to manufacture a final product. Innovation is curtailed by limits on how an individual action will interact with other components of the system. For example, the ability of a producer to switch to alternative crops for biofuels will require more than a single buyer in the marketplace, otherwise producers subject themselves to the prices the buyer is willing to offer in a non-competitive market, as well as price volatility from the supply chain of the buyer in using the stock for a biofuel, which may be subject to political uncertainty due to government subsidies and competing biofuel sources. In order to create incentives to cultivate alternative crops for a new market, the relative risk from entering these new markets will need to be offset. Private/public partnerships and policies that can explicitly support new technologies and bear the risk of innovation are beginning to enter policy discussions (see Leyden and Link 2015; Mazzucato 2013).

4. Scaling interventions

The level of risk associated with innovations in integrating waste in FEW systems will change with the scale of development. Trade-offs exist in the scale of the interventions intended to foster greater integration and feedback across the FEW sectors (Hill and Engle 2013). FEW systems exist at multiple spatial scales, from community and local government to state, regional, national, and international. What determines the appropriate scale of any policy intervention will depend on the size of three existing systems: natural (watershed, river basin, land), social (markets, communities, regional economies), and built systems (water infrastructure, energy grids, transportation network) relevant to the specific policy challenge (Wilson et al. 1999; Ostrom 2012).

Smaller scale interventions will tend to better fit local conditions while larger scaled innovations have the potential to achieve economies of scale and scope (Oates and Portney 2003; Kauneckis and Andersson 2009). In terms of environmental benefits, the regional scale (defined by climate and land use parameters) may grant the greatest overall gains due to regional differences in energy systems and hydrological regimes and food production; however, small scale (community level) systems allow for greater experimentation. Some combination of nested governance systems that recognizes the importance of local heterogeneity in natural systems, built infrastructure, and local preferences within large-scale systems of regulatory policy and national markets will certainly be necessary (Ferraro 2003; Adger et al. 2005).

One explicit trade-off in scaling systems is how to control "leakage," the phenomenon of forcing environmental externalities outside the system of study. Local systems that close the loop on waste may simply lead to larger waste streams outside the system. A second major challenge with utilizing current research on scaling policy interventions is how to incorporate the networked nature of modern economies and global supply chains.

Closing the loop on waste in value chains at the FEW nexus

Closed loop systems provide an opportunity to decrease the environmental impact of waste by-products while improving efficiencies in the production cycle. Figure 3 represents the four examples (described above) of potential waste streams being incorporated as inputs back into energy, food, and water systems. Each figure uses a modified version of a closed-loop

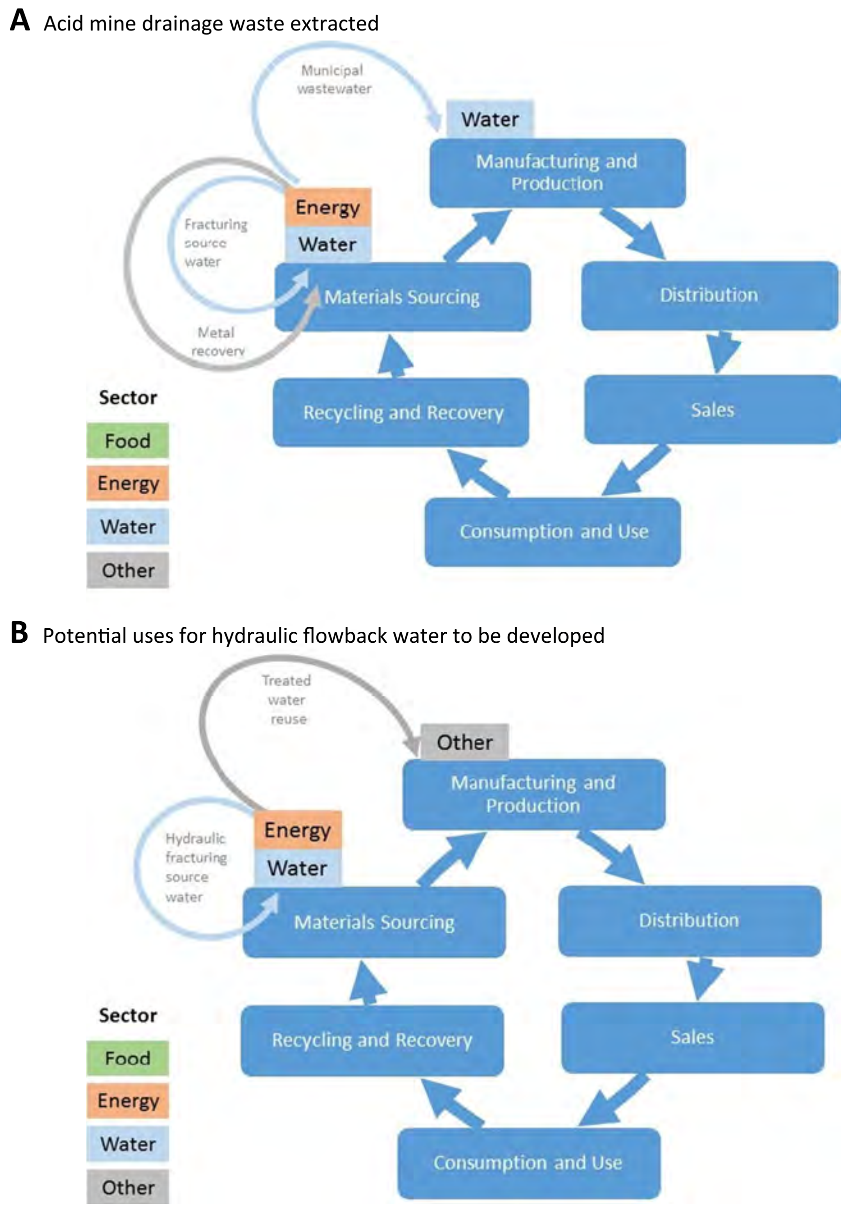

Fig. 3 Schematic of closed loop value chain for acid mine drainage (AMD) wastes (**a**), hydraulic fracturing flowback (**b**), anaerobic digestion (**c**), and crassulacean acid metabolism (CAM) plants for bioenergy on arid lands (**d**); each depicted in a life-cycle framework for closed-loop systems

value chain originally presented by the World Economic Forum (2009). There are six stages of the life cycle of a product: materials sourcing, manufacturing and production, distribution, sales, consumption and use, and recycling and recovery. While the examples discussed here primarily improve the material extraction and recycling/recovery stages, other waste products could be looped in to different stages of the life cycle. In order to illustrate interactions across FEW sectors, the sector in which the waste is produced is color coded and labeled in each figure, and the sector into which the waste product is being looped is color coded as food, energy, water, or other.

Figure 3a illustrates the potential loops of acid mine drainage wastes. The waste occurs at the nexus of energy and water in the materials sourcing phase of energy production from coal. The waste of AMD offers three potential loops back into production activities. These include the use of AMD in treating municipal wastewater, which uses a waste product from the energy sector directly as an input into the water sector. AMD is actively being explored for use in hydraulic fracturing as a water source. Finally, metal recovery from AMD has been used as a pigmentation material from a production cycle other than FEW.

Figure 3b represents the potential uses for waste water from hydraulic fracturing, both as re-usable source water for hydraulic fracturing activities and as treated water for reuse in other sectors. Both of which have significant technical

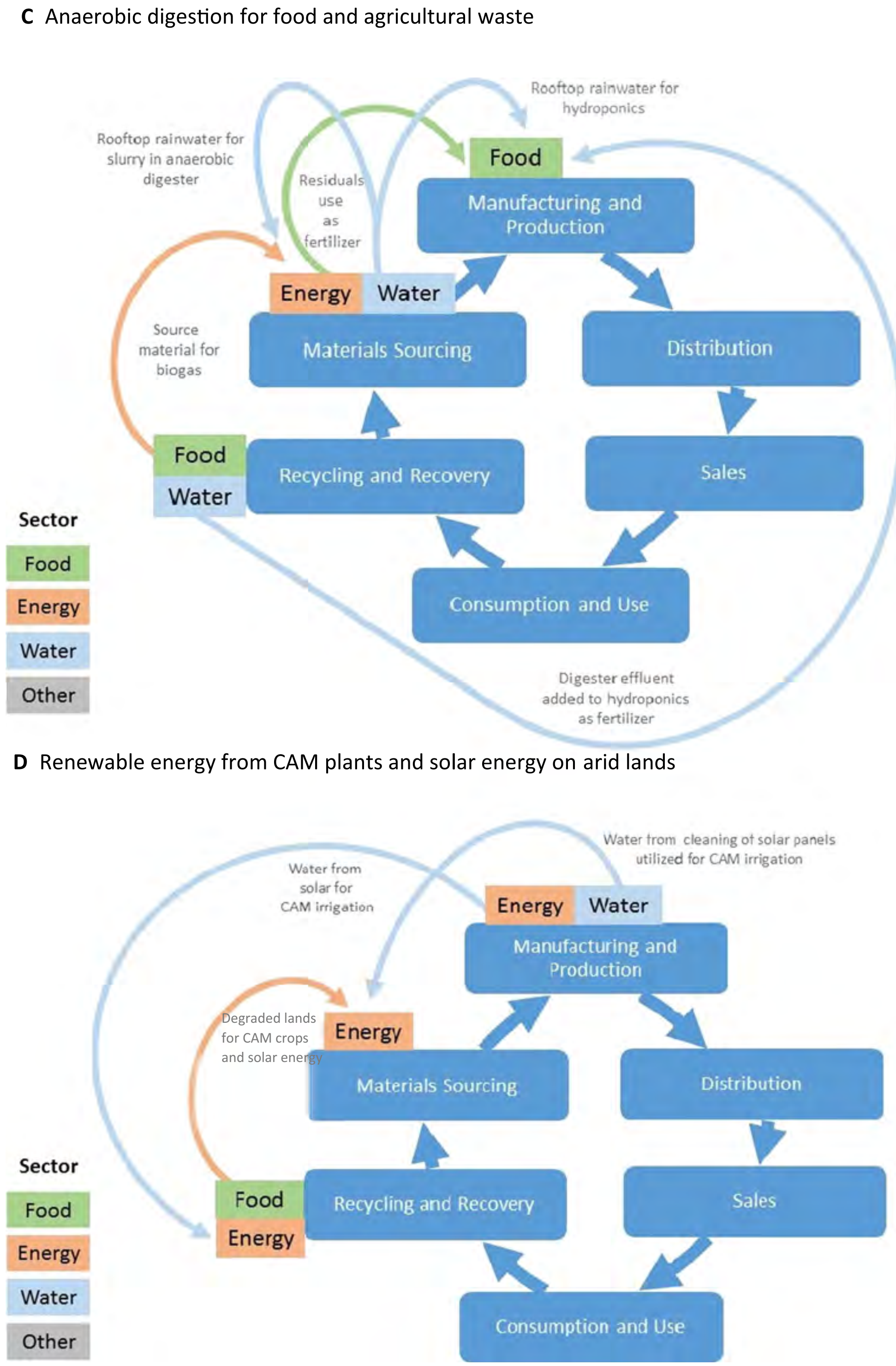

Fig. 3 (continued)

challenges in restoring water quality for either use. Solutions for waste reduction in this example have been the least developed. To contrast, anaerobic digestion systems by definition consume waste. Figure 3c shows how anaerobic digestion for the production of biogas links the food and energy sectors and reduces water consumption. Recycled food waste becomes source material for biogas production, and residuals from biogas can then be returned to the food system (or other agricultural production systems) as fertilizer. With integrative management of food and energy production in a greenhouse-like infrastructure (as depicting in Fig. 2), it is also possible to internalize water management and cycle water through both production systems (Fig. 3c).

Figure 3d includes the waste loops that can be accomplished through integrated renewable energy systems for arid regions. Degraded agricultural lands can be used for the growth of CAM crops that are then used for bioenergy production. This agricultural activity has the potential to replace agricultural systems with greater water input demands, reducing water consumption. Solar energy systems can be colocated CAM crops so that the water used in the maintenance of solar panels can provide the minimal irrigation needed for the crop. Additional value chains (not depicted) could be created through waste system loops in other phases of the life cycle.

Analyzing opportunities for closed-loop systems through a governance framework

Analyzing FEW systems through a governance framework is critical for understanding the potential of implementing emerging technologies and techniques. Challenges and opportunities for incorporating waste streams into and across FEW systems are globally common if locally specific, making this research widely applicable across a variety of scales and locations. Opportunities for integrated systems are often context-specific and depend on local conditions. The examples of AMD, biogas production, and the production of renewable energy on arid lands all involved local governance challenges.

When reviewing the example of AMD in light of the governance framework outlined here, a specific challenge for governance that would not necessarily apply in other examples emerges: how to assign responsibility for a legacy waste. AMD, a continuously generated waste that could have other uses, e.g., for pigment, phosphorus remediation, or fracturing water (Fig. 1), is the product of mining that occurred historically and the entities responsible are no longer liable in many cases. Neither is there any expectation of being able to end this waste stream. Coal mines are so extensive and continuous underground in the Appalachian Region for example that the source of the waste cannot be contained. Iron extracted from this waste may be a resource produced into the foreseeable future, but property right institutions and policy design will both require greater direct governmental and citizen involvement than cases where a manufacturer of waste can be directly involved. Long-term financing is essential and might be incentivized through economic stimulation associated with products. The scale of the resource in this case might be assumed as fixed if the current mining practices immediately remediate effects of new AMD under modern law.

In the case of biogas production that makes use of wastes from food systems and agriculture while yielding energy and fertilizer, governance issues are very different. The challenge for this system lies with unifying producers from economic sectors that have traditionally been isolated from one another. Contractually obligated property rights would incentivize the use of waste for value-added products. The "feebate" approach would allow partnering manufacturers to save costs for waste disposal by offsetting the cost with a subsidy directly linked to the usage of waste. The scale of development in this case should be expected to change because biogas production is not yet widely practiced in the USA.

Renewable energy production on arid lands might face fewer challenges for governance due to public perception of problems related to drought in this region. In the western United States at least, there are already practical incentives for reducing water consumption. Water resources are expensive, creating clear opportunity for technologies with lower production costs. Here, awareness of the best alternatives and most beneficial partnerships would require policy design that promotes research.

Vision for integrated systems that close the loop on waste in FEW requires a governance framework that encourages dialogue among traditionally independent sectors of the economy. Creative solutions for converting waste to resources in a closed-loop infrastructure demand institutional frameworks that reward internalized waste management and partnering of manufacturers. Figure 3 summarizes how integrated systems can be used to minimize externalities and promote waste as a resource. Every opportunity for integrative management would benefit from research that targets optimized solutions for closed-loop infrastructure because solutions, and partners capable of achieving them, have not yet been clearly identified in many cases (e.g., hydraulic fracturing). Research can benefit from the interdisciplinary perspective offered here that links technological innovation to a governance framework that encourages progress toward harmonized environmental and economic sustainability.

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Carbon Sequestration

University of California – Davis, 2021

What is Carbon Sequestration?

Carbon sequestration secures carbon dioxide to prevent it from entering the Earth's atmosphere. The idea is to stabilize carbon in solid and dissolved forms so that it doesn't cause the atmosphere to warm. The process shows tremendous promise for reducing the human "carbon footprint." There are two main types of carbon sequestration: biological and geological.

What is Carbon?

In many ways, carbon is life. A chemical element, like hydrogen or nitrogen, carbon is a basic building block of biomolecules. It exists on Earth in solid, dissolved and gaseous forms. For example, carbon is in graphite and diamond, but can also combine with oxygen molecules to form gaseous carbon dioxide (CO2).

Carbon dioxide is a heat trapping gas produced both in nature and by human activities. Man-made carbon dioxide can come from burning coal, natural gas and oil to produce energy. Biologic carbon dioxide can come from decomposing organic matter, forest fires and other land use changes.

The build-up of carbon dioxide and other **'greenhouse gases' in the atmosphere can trap heat and contribute to climate change**.
Learning how to capture and store carbon dioxide is one way scientists want to defer the effects of warming in the atmosphere. This practice is now viewed by the scientific community as an essential part of **solving climate change**.

Types of Carbon Sequestration

Biological

Biological carbon sequestration is the **storage of carbon dioxide in vegetation such as grasslands or forests**, as well as in soils and oceans.

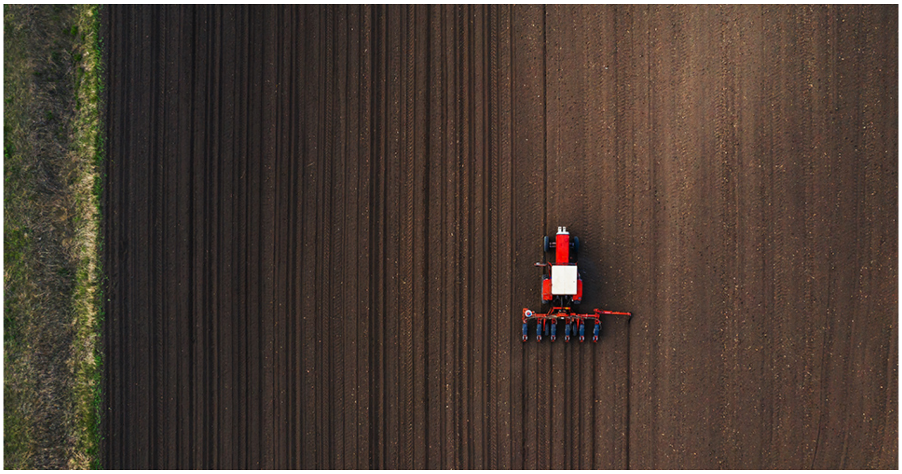
Biological Carbon Found in the Oceans

Oceans absorb roughly 25 percent of carbon dioxide emitted from human activities annually.

Carbon goes in both directions in the ocean. When carbon dioxide releases into the atmosphere from the ocean, it creates what is called a positive atmospheric flux. A negative flux refers to the ocean absorbing carbon dioxide. Think of these fluxes as an inhale and an exhale, where the net effect of these opposing directions determines the overall effect.

Colder and nutrient rich **parts of the ocean are able to absorb more carbon dioxide** than warmer parts. Therefore, the polar regions typically serve as carbon sinks. By 2100, most of the global ocean is expected to be made up of carbon dioxide, potentially altering the ocean chemistry and lowering the pH of the water, making it more acidic.

Biological Carbon Found in Soil



Carbon is sequestered in soil by plants through photosynthesis and can be stored as soil organic carbon (SOC). Agroecosystems can degrade and deplete the SOC levels but this carbon deficit opens up the opportunity to store carbon through new land management practices. Soil can also store carbon as carbonates. Such carbonates are created over thousands of years when carbon dioxide dissolves in water and percolates the soil, combining with calcium and magnesium minerals, forming “caliche” in desert and arid soil.

Carbonates are inorganic and have the ability to store carbon for more than 70,000 years, while soil organic matter typically stores carbon for several decades. Scientists are working on ways to accelerate the carbonate forming process by adding finely crushed silicates to the soil in order to store carbon for longer periods of time.

Biological Carbon Found in Forests

About 25 percent of global carbon emissions are captured by plant-rich landscapes such as forests, grasslands and rangelands. When leaves and branches fall off plants or when plants die, the carbon stored either releases into the atmosphere or is transferred into the soil. Wildfires and human activities like deforestation can contribute to the diminishment of forests as a carbon sink.

Biological Carbon Found in Grasslands

While forests are commonly credited as important carbon sinks, California's majestic green giants are serving more as carbon sources due to rising temperatures and impact of drought and wildfires in recent years. Grasslands and rangelands are more reliable than forests in modern-day California mainly because they don't get hit as hard as forests by droughts and wildfires, according to research from the University of California, Davis. Unlike trees, grasslands sequester most of their carbon underground. When they burn, the carbon stays fixed in the roots and soil instead of in leaves and woody biomass. Forests have the ability to store more carbon, but in unstable conditions due to climate change, grasslands stand more resilient.

Geological

Geological carbon sequestration is the process of storing carbon dioxide in underground geologic formations, or rocks. Typically, carbon dioxide is captured from an industrial source, such as steel or cement production, or an energy-related source, such as a power plant or natural gas processing facility and injected into porous rocks for long-term storage.

Carbon capture and storage can allow the use of fossil fuels until another energy source is introduced on a large scale.

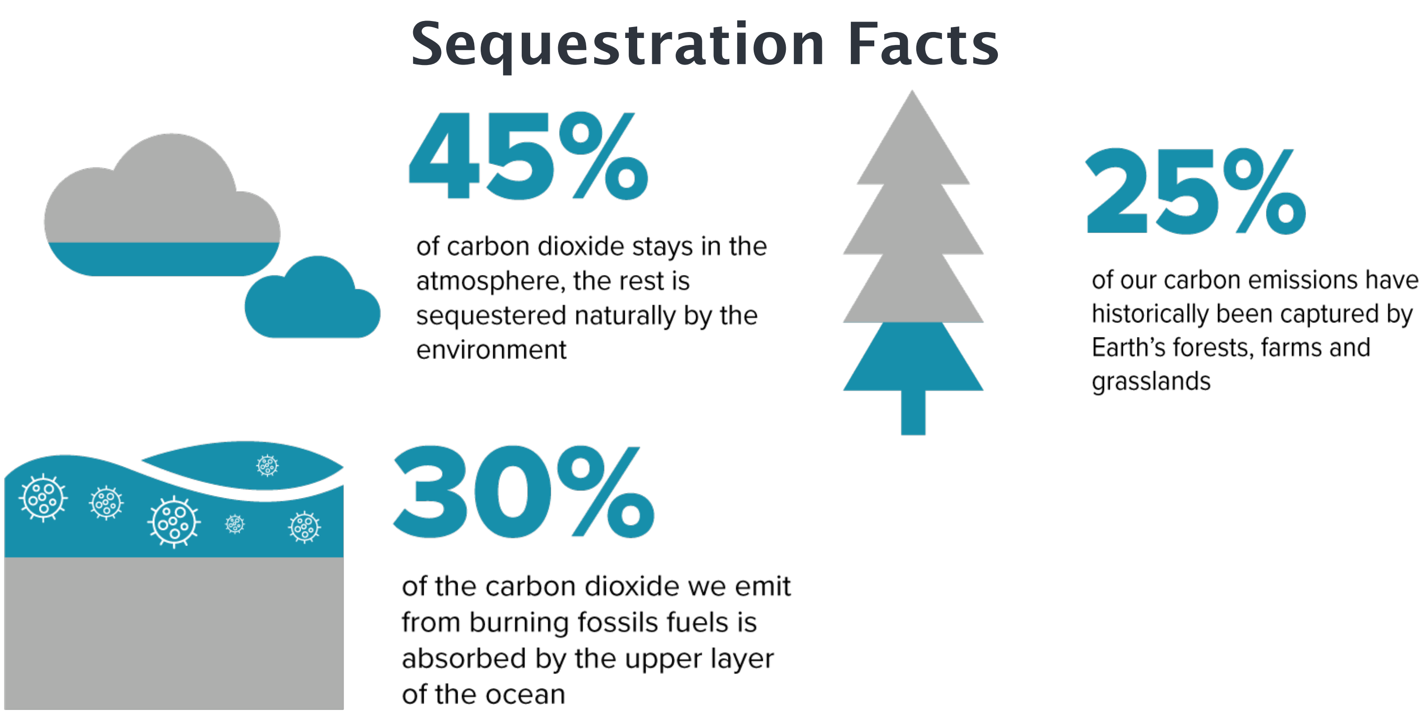
Technological

Scientists are exploring new ways to remove and store carbon from the atmosphere using innovative technologies. Researchers are also starting to look beyond removal of carbon dioxide and are now looking at more ways it can be used as a resource.

Graphene production: The use of carbon dioxide as a raw material to produce graphene, a technological material. Graphene is used to create screens for smart phones and other tech devices. Graphene production is limited to specific industries but is an example of how carbon dioxide can be used as a resource and a solution in reducing emissions from the atmosphere.

Direct air capture (DAC): A means by which to capture carbon directly from the air using advanced technology plants. However, this process is energy intensive and expensive, ranging from $500-$800 per ton of carbon removed. While the techniques such as direct air capture can be effective, they are still too costly to implement on a mass scale.

Engineered molecules: Scientists are engineering molecules that can change shape by creating new kinds of compounds capable of singling out and capturing carbon dioxide from the air. The engineered molecules act as a filter, only attracting the element it was engineered to seek.



The Future of Carbon Sequestration

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Impacts of Carbon Sequestration

- **About 25% of our carbon emissions have historically been captured by Earth's forests, farms and grasslands. Scientists and land managers are working to keep landscapes vegetated and soil hydrated for plants to grow and sequester carbon.**
- **As much as 30% of the carbon dioxide we emit from burning fossils fuels is absorbed by the upper layer of the ocean. But this raises the water's acidity, and ocean acidification makes it harder for marine animals to build their shells. Scientists and the fishing industry are taking proactive steps to monitor the changes from carbon sequestration and adapt fishing practices.**

G7 countries eye waste-to-energy incineration as part of plastic pollution solution

Ocean Plastics Charter calls for recycling or 'recovering' all plastics by 2040

Emily Chung · CBC News · Posted: Sep 21, 2018 4:00 AM ET | Last Updated: September 21, 2018

Waste-to-energy incineration — burning garbage and then using the resulting heat to keep buildings warm or generate electricity — is popular in some European countries. (Getty Images)

What to do with all those non-recyclable plastic forks, toys and broken patio chairs in our garbage? Canada and its G7 partners are looking at burning such plastics for energy — but the idea is still controversial.

Environment Minister Catherine McKenna is at the G7 environment ministers' meeting in Halifax this week, promoting an agreement that aims to reduce the amount of plastic waste humans churn out — more than 6 billion tonnes so far, including millions of tonnes that end up polluting the oceans each year.

Among other things, the Canada-led Ocean Plastics Charter announced in June calls for eliminating plastic from landfills, but allows for "waste-to-energy" incineration.

The non-binding charter, signed by G7 members Canada, France, Germany, Italy and the U.K. (but not Japan or the U.S.), includes commitments to:

- Work with industry toward 100 per cent reusable, recyclable or, where viable alternatives do not exist, recoverable plastics by 2030.
- Work with industry and other levels of government to recycle and reuse at least 55 per cent of plastic packaging by 2030 and recover 100 per cent of all plastics by 2040.

While the G7 doesn't define "recover" in its charter, Environment Canada confirmed by email that recovery refers to "all activities at the end of life that recover value from plastics waste," including burning it to generate energy or processing it into fuels. It does not include landfilling or incineration without capturing the resulting heat or energy.

A toy doll and other plastic waste, much of it non-recyclable, lie on a beach on the Freedom Island ecotourism area, near Manila, Philippines. The Canada-led Ocean Plastics Charter aims to reduce plastic pollution in the world's oceans. (Noel Celis/AFP/Getty Images)

That would mean a big change in the way we deal with plastics currently tossed into the garbage, from disposable cutlery and toothbrushes, to children's toys and broken patio furniture.

"The implications are there would have to be some more waste-to-energy facilities developed," said Virginia MacLaren, an associate professor of geography at the University of Toronto who studies waste management.

Popular in Europe

Waste-to-energy incineration — burning garbage and then using the resulting heat to keep buildings warm or generate electricity — is popular in some European countries. For example, 35.8 and 20.7 per cent of garbage in Norway and Denmark respectively was incinerated with energy recovery in 2014. Meanwhile, Sweden is known for importing garbage from other countries to fuel incinerators that provide district heating.

But in Canada, only about three per cent of municipal waste was incinerated at waste-to-energy facilities in 2006, the most recent year for which statistics were available.

Most Canadian incinerators are decades old, and MacLaren said three recent proposals in Ontario were cancelled (a fourth, the Durham York Energy Centre, was actually built) because of either one of the following:

- Financial problems: waste-to-energy incineration is typically about twice as expensive as landfilling.
- Concerns about having a reliable waste stream to fuel the incinerators in the future, given Canadians' efforts to reduce, recycle and move toward zero waste.

Less wasteful than landfilling

Still, a 2016 study that MacLaren co-authored found that among 217 residents surveyed in southern Ontario, a majority preferred waste-to-energy incineration to sending garbage to a landfill.

However, the study also supported one argument made by opponents of waste-to-energy incineration: It would cause people to recycle less. About 15 per cent of respondents agreed they probably *would* recycle less if they knew anything they threw in the garbage would go to a waste-to-energy incinerator.

Konrad Fichtner is a Vancouver-based consultant with Morrison Hershfield who advises municipalities and regions around the world on waste-management plans and technologies, especially incineration, waste-to-energy and composting.
Recovering the energy from the waste that's left over after we've recycled and composted everything we can makes more sense than landfilling, he said.

"Once it's in the ground, it's going to stay there — and that's a waste."

A 2016 survey of Ontario residents suggested that people would prefer sending their trash to a waste-to-energy incinerator over a landfill. But some said they would recycle less if they knew that's where their trash was going. (Colleen Connors/CBC)

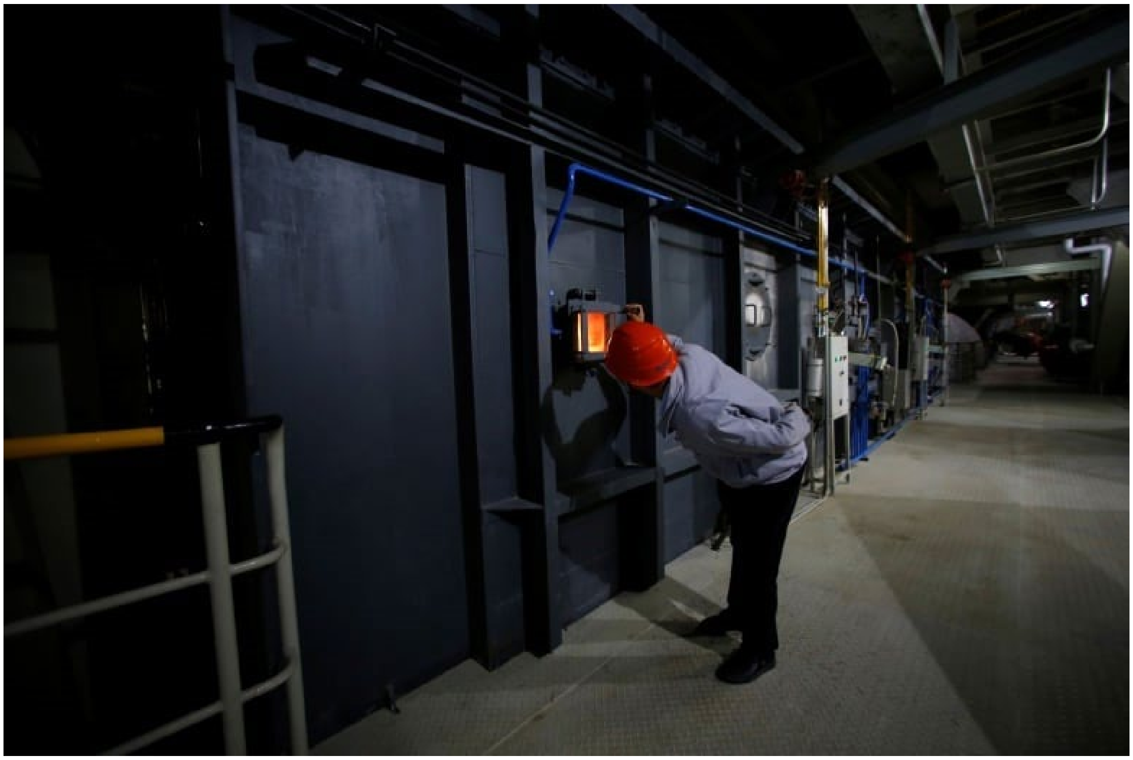
Even landfills that capture the greenhouse gases released as the trash decomposes capture only a fraction of the energy that could be recovered through incineration, he said, and much of that landfill gas is flared off, rather than being used for heating or electricity.

While in the past, people tended to be concerned about the air pollution generated from incinerators, Fichtner said with better technology and stricter regulations, that's no longer much of a concern.
"They have been cleaned up," he said. "Would I have trouble raising my family next to an incinerator? No, absolutely not; I wouldn't mind that at all."

Ashley Wallis, water and plastics program manager for the environmental advocacy group Environmental Defence, agreed that pollution from incinerators is no longer a big concern.

But Environmental Defence is still opposed to incineration because it says the option:
- Incentivizes waste production.
- Disincentivizes investment in recycling innovation.
- Is inconsistent with a "circular economy" — a way to improve sustainability and ultimately eliminate waste by constantly reusing and recycling resources, such as plastics.

"Once you burn plastics, those molecules are no longer available to make new plastic products," Wallis said. That means we'll continue to need to extract more oil to make new plastics instead.



An employee works inside a newly launched waste-to-energy plant in Suzhou, China. (Aly Song/Reuters)

Wallis was in Halifax this week to see what Canadian policies would be announced at the G7 environment ministers' meeting in support of the plastics charter.

The charter does include some positive commitments, such as targets for recycled content in new plastic products and targets for what proportion of plastic gets recycled, she said. But her group was "a little disappointed" by the inclusion of waste-to-energy as a solution.

Despite its appearance in the charter, Fichtner doesn't see a big future for waste-to-energy incineration, largely because of the cost. The World Bank says it is typically double the cost of sending trash to the dump.

In Canada, Fichtner says, a waste-to-energy incinerator can take 25 years or more to pay off. At a time when municipalities are hoping to have zero waste 25 years in the future, that's not an investment many are willing to make.

New technologies

But new energy "recovery" technologies, other than traditional incineration, may be on the horizon. A plant is being built in Edmonton by Enerkem will convert trash into ethanol through a process called fluidized bed gasification, although the project has been plagued by delays and budget overruns.

A plant is being built in Edmonton to convert trash into ethanol through a process called fluidized bed gasification, though the project has been plagued by delays and budget overruns. (Enerkem)

And Sustane Technologies is building a plant in Nova Scotia that aims to convert plastic — especially film plastics, like plastic bags, that are hard to recycle — into synthetic kerosene and diesel through a process called pyrolysis.

In theory, synthetic fossil fuels produced in such processes could be converted back into plastics, although they're generally burned instead.

Right now those technologies are very expensive. But Fichtner says he's keeping an eye on developments.

"I think, ultimately, someone is going to come up with a process that is more efficient, and will be able to handle a single waste stream, such as plastics, in an efficient manner," he said. "And I'm looking for that; I'm hoping to see it soon."

In the meantime, both MacLaren and Wallis say we need to do better at eliminating waste to begin with, by making sure the waste we create is made of materials that can be recycled.

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The Composting Process

What is compost?

Compost is decomposed organic material. Compost is made with material such as leaves, shredded twigs, and kitchen scraps from plants.

To gardeners, compost is considered "black gold" because of its many benefits in the garden. **Compost is a great material for garden soil.** Adding compost to clay soils makes them easier to work and plant. In sandy soils, the addition of compost improves the water holding capacity of the soil. By adding organic matter to the soil, compost can help improve plant growth and health.

Composting is also a good way to recycle leaves and other yard waste. Instead of paying a company to haul away leaves, you can compost the leaves and return the nutrients to your garden. Instead of buying peat moss, save money and make your own compost!

The composting process

The composting process involves four main components: **organic matter**, **moisture**, **oxygen**, and **bacteria**.

Organic matter includes plant materials and some animal manures. Organic materials used for compost should include a mixture of brown organic material (dead leaves, twigs, manure) and green organic material (lawn clippings, fruit rinds, etc.). Brown materials supply carbon, while green materials supply nitrogen. The best ratio is 1 part green to 1 part brown material. Shredding, chopping or mowing these materials into smaller pieces will help speed the composting process by increasing the surface area.

For piles that have mostly brown material (dead leaves), try adding a handful of commercial 10-10-10 fertilizer to supply nitrogen and speed the compost process.

Moisture is important to support the composting process. Compost should be comparable to the wetness of a wrung-out sponge.

If the pile is too dry, materials will decompose very slowly. Add water during dry periods or when adding large amounts of brown organic material.

If the pile is too wet, turn the pile and mix the materials. Another option is to add dry, brown organic materials.

Oxygen is needed to support the breakdown of plant material by bacteria. To supply oxygen, you will need to turn the compost pile so that materials at the edges are brought to the center of the pile. Turning the pile is important for complete composting and for controlling odor.

Wait at least two weeks before turning the pile, to allow the center of the pile to "heat up" and decompose. Once the pile has cooled in the center, decomposition of the materials has taken place. Frequent turning will help speed the composting process.

Bacteria and other microorganisms are the real workers in the compost process. By supplying organic materials, water, and oxygen, the already present bacteria will break down the plant material into useful compost for the garden. As the bacteria decompose the materials, they release heat, which is concentrated in the center of the pile.

You may also add layers of soil or finished compost to supply more bacteria and speed the composting process. Commercial starters are available but should not be necessary for compost piles that have a proper carbon to nitrogen ratio (1 part green organic material to 1 part brown organic material).

In addition to bacteria, larger organisms including insects and earthworms are active composters. These organisms break down large materials in the compost pile.

How long does it take?

The amount of time needed to produce compost depends on several factors, including the size of the compost pile, the types of materials, the surface area of the materials, and the number of times the pile is turned.

For most efficient composting, use a pile that is between 3 feet cubed and 5 feet cubed (27-125 cu. ft.). This allows the center of the pile to heat up sufficiently to break down materials.

Smaller piles can be made but will take longer to produce finished compost. Larger piles can be made by increasing the length of the pile but limiting the height and the depth to 5 feet tall by 5 feet deep; however, large piles are limited by a person's ability to turn the materials. You may also want to have two piles, one for finished compost ready to use in the garden, and the other for unfinished compost.

If the pile has more brown organic materials, it may take longer to compost. You can speed up the process by adding more green materials or a fertilizer with nitrogen (use one cup per 25 square feet).

The surface area of the materials effects the time needed for composting. By breaking materials down into smaller parts (chipping, shredding, mulching leaves), the surface area of the materials will increase. This helps the bacteria to more quickly break down materials into compost.

Finally, the number of times the pile is turned influences composting speed. By turning more frequently (about every 2-4 weeks), you will produce compost more quickly. Waiting at least two weeks allows the center of the pile to heat up and promotes maximum bacterial activity. The average composter turns the pile every 4-5 weeks.

When turning the compost pile, make sure that materials in the center are brought to the outsides, and that materials from the outside edges are brought to the center.

With frequent turning, compost can be ready in about 3 months, depending on the time of year. In winter, the activity of the bacteria slows, and it is recommended that you stop turning the pile after November to keep heat from escaping the pile's center. In summer, warm temperatures encourage bacterial activity and the composting process is quicker

Using compost in the yard

Incorporate compost into your garden as you prepare the soil in the spring. Cover the area with 3-4 inches of soil and till it in to at least the upper 6 inches of soil. Add compost to soil in vegetable gardens, annual flower beds, and around new perennials as they are planted.

You may also use compost as mulch around flower beds, vegetable gardens, or around trees or shrubs in landscape beds. Apply a 3 inch layer. Be careful not to apply mulch close to the main stem or trunk of the plant.

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Layering Compost

Layering is the recommended method for starting a compost pile. Layering is similar to making lasagna, as you add thin, uniform layers of materials in a repeated pattern. Once the compost pile is active, you can incorporate new material into the center of the pile or you can mix it in when turning the pile.

Start your compost pile on bare ground, removing the sod or existing vegetation. Contact with the soil will provide bacteria needed for composting. Do not place the pile on concrete or asphalt. You may also place a pallet underneath the pile if poor drainage beneath the pile is a concern.

Layer 1

Add a 6-8 inch layer of organic matter, both brown and green. Do not pack the materials in, as this limits air flow and oxygen needed by bacteria.

Layer 2

Add a starter material, such as animal manures (see the list of acceptable types), fertilizers, or commercial starters. These materials help to heat up the pile by providing nitrogen for the bacteria and other microorganisms.

Select one of the following:

- 1-2 inch layer of fresh manure from a grain eating animal, OR
- 1 cup of 10-10-10 or 12-12-12 fertilizer per 25 square feet, OR
- a commercial starter (follow label directions)

Layer 3

Add a 1-2 inch layer of top soil or finished garden compost. This is done to introduce the microorganisms to the pile. Avoid using soil recently treated with insecticides and also avoid using sterile potting soil.

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What to Compost

You may use:

- Leaves
- Some manures (cow, horse, sheep, poultry, rabbit, llama)
- Lawn clippings
- Vegetable or fruit wastes, coffee grounds
- Shredded newspaper or white, unglazed office paper
- Trimmed plant materials
- Shredded stems and twigs

Don't use:

- Meat or dairy scraps
- Some manures (cat, dog, swine, and carnivore manures)
- Glazed, color printed magazine paper
- Diseased plants or plants with herbicides applied

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Types of Compost Bins

Holding units are low maintenance, and are good choice for those with limited space, such as apartment dwellers. These units do not require turning, however the lack of aeration causes the composting process to take 6 months to 2 years. Holding units are available from stores and catalogs.

Portable bins are similar to holding units, except that they can be taken apart and moved. Materials can also be mixed with this type of bin. Plastic units are available for purchase, or you may construct a bin from wire fencing framed in wood.

Turning units are designed so that they may be aerated. Turning units produce compost faster because they supply oxygen to the bacteria in the pile. These units may also have less odor problems, which are associated with poor aeration.

Turning units may be either a series of bins or a structure that rotates, such as a ball or barrel. These systems often cost more and are more difficult to build. Materials must also be saved until a unit can be filled to the correct level. Once these units are filled and the turning process begins, new materials should not be added.

Heaps are an option for those who do not wish to build or purchase a bin structure. Turning the heap is optional, but remember the composting process will be slowed if the pile is not turned. Woody materials may take a very long time to decompose with this method, and food scraps may attract pests.

Sheet composting can be done in the fall. With this method, a thin layer of materials such as leaves (that have not been composted) are worked into the garden. By spring, the material will be broken down. The decomposition process ties up soil nitrogen, making it unavailable to other plants. Because of this, sheet composting should only be done in the fall when the garden is fallow.

Soil incorporation is also known as **trench composting**. Organic material are buried in holes 8-15 inches deep, and then covered with soil dug from the hole. Decomposition takes about a year, as limited oxygen slows the process. It is recommended to avoid planting that area for a year, as the nitrogen available to plants may be limited by the decomposition process.

Where to place the compost

Placing the compost bin in your yard depends on both functional and aesthetic needs.

For the compost bin to function properly, place the compost pile in an area with good air circulation. Do not place the pile so that it is in direct contact with wooden structures, as this will cause decay. It is best to locate the pile in partial shade, but this is not a necessity.

You may want to locate it close to the garden and close to a water source. If kitchen scraps will be added regularly, it may be more convenient to have the pile near the kitchen.

You may also want to screen the pile from view with a fence or by placing it behind shrubs or a taller structure. You may also wish to avoid placing the pile near outdoor entertaining areas.

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Compost Troubleshooting

The compost has a bad odor

Problem: Not enough air. Not enough water. Too small.
Solutions: Turn it, add dry material if the pile is too wet.

The center of the pile is dry

Problem: Lack of nitrogen.
Solutions: Moisten and turn the pile.

The compost is damp and warm only in the middle

Problem: Pile is too small.
Solutions: Collect more material and mix the old ingredients into a new pile.

The heap is damp and sweet-smelling but still will not heat up

Problem: Lack of nitrogen.
Solutions: Mix in a nitrogen source like fresh grass clippings, manure or fertilizer.

Large, undecomposed items are still in the mix

Problem: Low surface area.
Solutions: Remove items, and chop or shred large items.

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Common Questions

Are oak leaves too acidic to be used for compost?

No, oak leaves in compost will not create an acidic soil. However, you need to be careful when applying walnut leaves because they contain a growth inhibitor to which some plants are sensitive. Walnut leaves must be thoroughly composted before applied to the garden.

Are there any plants that I should not use compost around?

The pH of compost is slightly basic (or alkaline), thus avoid adding compost to acid loving plants such as azaleas or hollies.

Can I add sawdust to the compost pile?

Yes, sawdust can be added to the compost pile. However, compost has a very high amount of carbon, so if you add sawdust, add nitrogen (such as a cup of 10-10-10 fertilizer per 25 square feet). To be safe, avoid adding sawdust from lumber treated with CCA (chromated copper arsenic).

How do I know when compost is ready?

Compost is ready to use when it is dark brown, crumbly and has an earthy odor. Compost is ready when it is fluffy, and should not be powdery. The original materials that were put into the compost pile should not be recognizable, except for small pieces of stems.

Can I add weeds to the compost pile?

Weeds will not be a problem for compost piles that heat up properly. However, if the pile does not reach high enough temperatures, weed seeds may not be destroyed and could pose a future problem.

Composting with Worms

EM 9034 • October 2011

Sam Angima, Michael Noack, and Sally Noack

What is composting with worms?

Photo by Michael Noack and Sally Noack. Used by permission.

Composting with worms (also called **vermicomposting**) is usually done with the common red wiggler worm (*Eisenia fetida*). This worm's specialized digestive system converts food waste and other organic materials to a nutrient-rich compost called **vermicast** or **worm castings**. It thrives in an **aerobic** (with air) environment. It is able to process large amounts of food waste and rapidly reproduce in a confined space.

What is the difference between conventional composting and vermicomposting?

Conventional or "hot" composting depends on the heat generated by a wide range of microorganisms, largely bacterial, that help convert organic waste to compost. The carbon-to-nitrogen ratio of the composting materials, combined with a balance of moisture and air, are very important factors in producing the heat that promotes composting and kills weed seeds. If done correctly, it is a very fast process (about 6 to 8 weeks under optimum conditions).

Vermicomposting is considered a "cold" composting process. There is no noticeable heat generated by bacteria during the decomposition process. Vermicomposting materials (food scraps and bedding) are generally lower in the carbon-to-nitrogen ratio than "hot" compost. Instead of heat, the vermicomposting process relies on micro- and macroorganisms, including worms. It is a relatively slow process (it can take up to 6 months for finished worm compost), and it does not destroy weed seeds. It provides up to 4 percent more nitrogen in the final compost than conventional "hot" compost and can be done inexpensively, in a small space, with little effort.

Why should I vermicompost?

Most food waste in the United States is sent to landfills and makes up 20 percent (by weight) of all landfill materials. When this food decomposes in a landfill, it produces methane gas. Methane is a greenhouse gas (a gas

Contents

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that traps heat in the atmosphere). Methane is about 20 times more potent than carbon dioxide, in terms of its warming potential.

Vermicomposting recycles organic waste that may otherwise end up in landfills. It is an easy process, compared to conventional composting, which requires frequent turning and the management of complex ratios of materials. Vermicomposting is also ideal for those who don't have a place for a regular compost bin (such as apartment dwellers). As a bonus, vermicast provides many beneficial microorganisms and nutrients to the soil, including beneficial bacteria, fungi, and protozoa as well as nitrogen, phosphorus, potassium, calcium, and magnesium.

What materials do I need for vermicomposting?

You need:

- a worm bin (pages 2–5)
- worms (pages 6–7)
- biodegradable bedding (pages 7–8)
- some form of grit (page 8)
- food (pages 8–9)

On the following pages, you'll find details and steps to take to ensure that your vermicomposting setup is successful.

The Worm Bin

Where should I keep the worm bin?

Before you choose the type of bin you want to use, consider where you will place it.

Indoors

A well-tended worm bin is odorless. You can keep it in a pantry, utility room, or under the kitchen sink. A garage, basement, or carport is also a potential site.

Outdoors

Worms thrive in temperatures between 55 and 77°F. So, if you keep your bin outside, you'll need to protect it from extreme temperatures. The north side of a structure (such as a house, shed, or garage) is preferred, because temperatures there don't fluctuate as much. The bin also needs protection from rain and wind. Place it under the eaves or a deck, or build a cover that repels rain but still allows good air circulation. An outdoor bin must also be secured against rodents, raccoons, and other animals.

Depending on your local climate, you may choose to place your worm bin outside during the warmer months and bring it in under cover during the cooler months. Be sure to put the bin in a place you visit often!

What size worm bin should I have?

To figure out the bin size you need, you must first determine the amount of food waste your family generates in 1 week. Your worm bin must contain 1 cubic foot of space for each pound of kitchen waste. Note that this does not mean that the bin would always be full, but rather that it would provide ample space for worms to work at the right moisture and oxygen levels.

You'll need approximately 1 cubic foot of bin space and 1 pound of food waste for each pound of worms you maintain. (There are about 1,000 worms per pound.) Be sure to follow this rule to avoid an overloaded or undernourished system. Too much food may result in overfeeding and harmful anaerobic conditions for the worms. Too little food slows the worms' growth and reproduction and contributes to their demise.

A 14-gallon worm bin measuring 1 foot deep by 1 foot wide by 2 feet long (1' x 1' x 2') gives you 2 cubic feet of volume, space for 2 to 2½ pounds of worms (see figure 1). A system this size can process 2 pounds of kitchen waste per week, approximately what the average family of two or three produces. A family of four to six would need a larger bin—6 cubic feet (1' deep x 2' wide x 3' long)—and more

Photo by Sam Angima, © Oregon State University.

Figure 1. Two 14-gallon plastic totes, modified to make a worm compost bin. Notice the ventilation holes lined with fine mesh screen to prevent small flies from getting in and worms from getting out.

worms (up to 6 pounds) to process about 6 pounds of kitchen waste per week.

Notice that in both cases the container depth stays the same. Because red wiggler worms dwell near the surface of the soil in nature, their survival in a worm bin requires that the bin space be no more than 1 foot deep. This allows for healthy aerobic conditions in the worm bin habitat.

Make sure to prepare the bin before your worms arrive. Don't worry if your measurements or methods are not exact. The worms won't notice!

What materials should I use to build it?

You can use a variety of materials to build a worm bin. Plastic totes, wooden bins, and commercial, stackable worm towers all are popular (Table 1). You also can use a shipping crate or food storage barrel—a great way to repurpose and recycle one. Just be sure that the wood was not treated with chemicals and that other toxic materials have not been stored in the containers (food grade is best).

Plastic totes

Most worm bins are made from plastic totes. Worms are very sensitive to light, so be sure the container is opaque and has a lid. The lid should fit snugly on the bin to prevent worms from escaping and unwanted pests from getting in. There are many different designs available. This publication focuses on the two-plastic-tote bin system (figure 1), because it is relatively low cost and easy to make.

To build this system, choose two sturdy, opaque plastic totes (with tops) of the same size (14-gallon is a good size to start with). The first tote is the vermicomposting bin (or worm bin) (figure 2). It nests inside the second tote, which collects any **leachate** (liquid residue) (figure 3) from the composting process. Note the spacers at the bottom

Photo by Bill Biernacki. Used by permission.

Figure 2. Vermicomposting bin system showing arrangement of two plastic totes stacked together. The first tote (the top one) is the vermicomposting bin. It has the ventilation holes and is the one that houses the worms.

Photo by Bill Biernacki. Used by permission.

Figure 3. In a vermicomposting system, leachate collects in the bottom plastic tote. Note the two plastic blocks set inside the bottom that help prevent the two totes from sticking to one another. This makes it easier to separate them for maintenance and cleaning.

Table 1. Characteristics of wood and plastic bins for vermicomposting.

Wood bin	Plastic bin
Natural material	Durable
Can be cut to any size	Space efficient
Breathes. Allows for evaporation during hot weather	Need to be sure it drains well
May dry out in extreme heat	Retains moisture well
Eventually degrades	May become too wet
Not easily movable	Clean and neat

of the second bin. They keep the top bin from sticking and make it easy to lift out. Use plastic for spacers. Wood and bricks are hard to clean.

Drill up to 20 ¼-inch holes in the bottom of the first tote (figure 4). These holes allow for drainage. If you have commercial vents (figure 5) for air circulation, drill four (or more) 1-inch holes for them along the top edge of the first bin. Otherwise, drill up to 10 ¼-inch holes on the sides, 2 to 3 inches below the lip of the tote (figure 6), for ventilation. You can drill up to five 1-inch holes fitted with vents on the lid of the vermicomposting bin (figure 2) to aid in air circulation. If you do this, be sure that the bin is not left out in the rain. If you wish, you can install a drain plug (figure 7) on the second bin to make it easier to drain the leachate.

Stacking tray system

The stacking tray system operates on the fact that worms follow food. Put bedding and worms in the bottom tray along with food scraps (figure 8, page 5). Once the food scraps are converted to compost, the worms look for a new source of food. Stack a new tray of fresh bedding and food scraps on top of the first tray. The worms wriggle their way through small holes in the bottom of the top tray (figure 9, page 5) to get to the food above. You harvest the compost in the first tray, and keep stacking new trays on top. Most have a drainage tray (figure 10, page 5) at the very bottom to collect leachate.

Photo by Michael Noack. Used by permission.

Figure 4. Drill up to 20 ¼-inch drainage holes in the bottom of the first tote. Notice that most of the holes are drilled in what are the lowest places on the tote's bottom. Leachate drains down to the lowest areas and out, so it won't stagnate in the worm bin.

Photo by Sally Noack. Used by permission.

Figure 5. Commercial vents fit into 1-inch holes.

Photo by Sam Angima, © Oregon State University.

Figure 6. If commercial vents are not available, drill up to 10 ¼-inch holes on the sides, 2 to 3 inches below the lip of the tote. You can glue screen material to the holes to prevent fruit flies from invading the system.

Photo by Sam Angima, © Oregon State University.

Figure 7. You can install a drain plug on the second bin to make it easier to drain leachate.

Other homemade bins

Probably the most well-known type of worm bin is a wooden box (1 foot deep x 2 feet wide x 3 feet long) with drainage holes drilled in the bottom and a hinged lid for access. Wooden bins breathe and have few odor or excess moisture problems. The main drawback is their weight. Installing wheels on the bottom of wooden bins makes them easier to move.

You can find plans for home-built plastic and wooden bins from the University of Kentucky Extension Service at http://www.ca.uky.edu/enri/enri312rev.pdf.

Do **not** use pressure-treated wood for worm bins. The chemicals are toxic to the worms. Suitable construction materials include exterior-grade plywood or construction-grade lumber. Wood that contains a natural pest deterrent (such as cedar, redwood, and cypress) may be toxic to worms.

If you paint the outside of your bin, leave the inside unpainted. White paint on the outside of the bin helps reflect light, keeping the worm bin cool in summer.

Photo by Sam Angima, © Oregon State University.

Figure 8. A commercial stacking tray system. Starting from the bottom, a series of trays are filled sequentially with food. As worms move upwards to fresh bedding and food, vermicast can be harvested from the bottom trays.

Photo by Sam Angima, © Oregon State University.

Figure 9. The trays in a stacking system are removable and have holes large enough to allow worms to move freely from one tray to the next.

Photo by Sam Angima, © Oregon State University.

Figure 10. The bottom of a stacking tray system is designed to capture leachate and allow its easy removal with a spout.

The Worms

Worm biology and other important facts

The most effective worm for vermicomposting in a bin is the red wiggler worm (*Eisenia fetida*), also known as manure worm, red worm, or tiger worm. In nature, red wiggler worms are specialized surface dwellers (**epigeic**). They live in the upper layers of the very rich organic matter in decaying litter piles. They do not develop burrows and aren't found deep in the subsoil, as are common garden earthworms. These attributes make the red wiggler appropriate for worm bin composting. Earthworms will not survive in the environment of an indoor worm bin.

Red wiggler worms tolerate a temperature range of 40 to 90°F, but they do best between 55 and 77°F. Peak composting and reproduction occur between 71 and 89°F. Below 50°F, the worms feed less and become less active. Red wiggler worms are about 75 to 90 percent water by weight. Be sure to keep the right level of moist environment in the bedding so that the worms don't dry out. These worms prefer a pH of about 5.5 but can tolerate a pH range from 4 to 9.

Red worms breathe through their skin. Although they have no "eyes," their skin cells are very sensitive to light (**photophobic**). Use an opaque bin and lid that exclude light. Vent holes and fluffed-up bedding provide ventilation and aerobic conditions.

E. fetida has often been described as a "tube with a gut" (figure 11). A red wiggler worm can eat as much as its own body weight in decaying organic material every day. Its intestinal tract contains approximately 1,000 times more microbial life than the food it consumes. In fact, it's not the food scraps themselves the worms are after, but the protozoa, fungi, and other microbes that are their actual diet. The worms ingest some of the decomposing waste along with the microbes.

Red worms are a type of annelid worm, characterized by their internal and external segmentation (or rings). Each segment contains a pair of kidneys. Liquid waste is eliminated through the skin.

Red worms have no teeth. Like a bird, they possess a crop and gizzard (figure 11). As food moves through the crop and gizzard, it mixes with grit and is macerated by the musculature in these organs.

Red wiggler worms reproduce rapidly after they reach sexual maturity (usually 30 to 45 days after hatching). They can double their population in about 60 days! They are **hermaphroditic**, which means that each worm has both sexes. But, a worm must mate with another worm to reproduce. In simple terms, each worm transfers its sperm to the other as they lie head to tail next to each other. A mucous collar is produced by the **clitellum** (a raised band circling the worm's body) which eventually forms a cocoon. A cocoon is smaller than a grain of rice. A mature worm can produce up to four yellow, lemon-shape cocoons per week (100 per year), hatching two to five worms in about 3 weeks. Young worms are whitish with a central pink tinge showing their blood vessels.

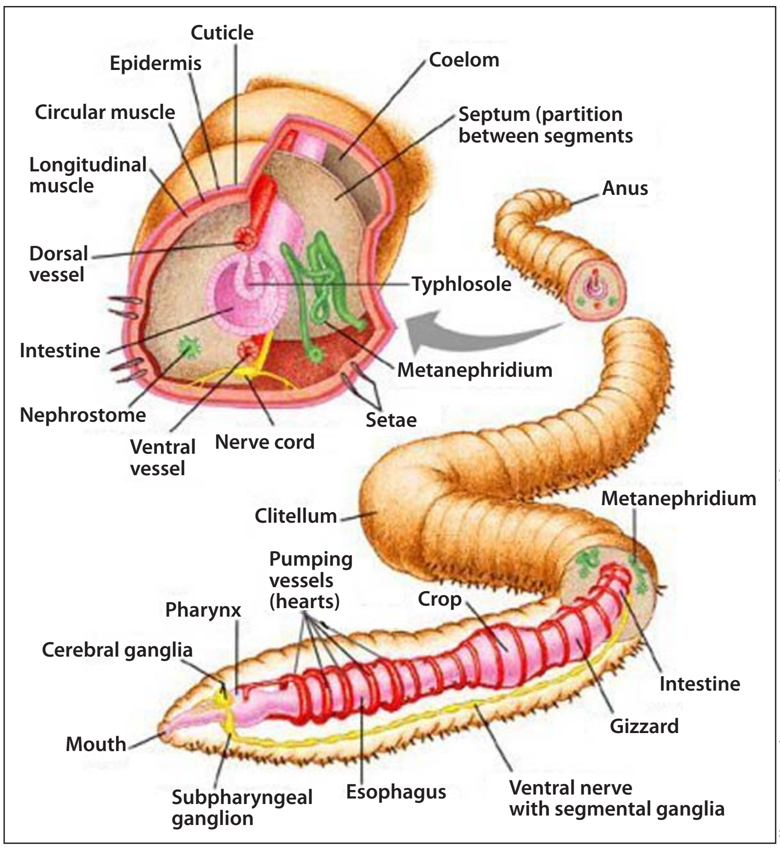

Illustration by Kingston Worm Farm. Used by permission.

Figure 11. Specialized digestive structure of a red wiggler worm (*Eisenia fetida*).

Where do I get the worms?

You can get red wiggler worms from a variety of sources. You can find commercial worm growers (vermiculturists) online who provide a mail-order service. Whenever you buy worms, whether from a commercial or private source, be sure to check that they are selling the right species (you want *Eisenia fetida);* the seasonal availability (since worms are most active during spring, summer, and fall); and their shipping methods. Also be aware that the pound of worms you order may not contain 1,000 worms—some bedding will be in the mix. Order only from reputable suppliers, and be sure to research their cultural methods (such as how they raise the worms and what and how they feed them). Check whether other customers have been pleased with their products.

Other sources of worms you may consider include your outdoor compost or manure pile, a friend or neighbor's vermicompost bin, your local Extension Master Gardener program, or a local solid waste district. Remember that the common earthworm or European nightcrawler (*Lumbricus terrestris*) is a subterranean, burrowing worm and is not the worm you want for vermicomposting.

Adding the worms

Once you have set up your vermicompost bin and have your worms, there are at least three methods of introducing worms into their new environment.

- Add kitchen scraps to fresh bedding and allow them to decompose for a few days before adding the worms.
- Add worms to fresh bedding and allow them to acclimate for a few days before feeding.
- Introduce worms and food scraps at the same time.

No matter which method you choose, be sure to observe the worms every day for a few weeks to see how they are feeding.

Bedding

The bedding in your worm bin provides a balanced diet and a damp, aerated home for your worms. You need enough bedding to cover the bottom of the worm bin to a depth of 4 to 6 inches.

Dry materials

It's best to include several different materials in the bedding. Mix at least two or three of the following materials for good bedding:

- **Shredded newspaper or recycled printer paper.** Do not use glossy paper. Shred paper by hand or machine (figure 12), but do not use cross-cut shredded paper. Cross-cut shreds are rectangular or diamond-shape and may increase compaction in the bin.
- **Corrugated cardboard.** Use small pieces.
- **Straw.** Don't use hay that has seed in it.
- **Coir (coconut fiber).** You can get this at nurseries and online.
- **Shredded leaves.** It's best to put in partially decomposed leaves. Check carefully for pests such as slugs and snails.
- **Sawdust.** Use sawdust only in small amounts, as it can become compacted.

Photo by Michael Noack. Used by permission.

Figure 12. Always use hand- or machine-shredded newspaper or recycled printer paper. Do not use glossy paper or cross-cut shredded paper.

Some people have found that adding a handful of alfalfa meal or pellets helps stabilize the microorganisms that partially decompose food scraps. This helps the worms get established in their new home. Do not use green grass clippings, because they may create too much heat as they decompose.

Grit

Remember that worms have a gizzard similar to birds and need grit to help break up food particles. Add a little grit (about ½ cup to a 14-gallon bin) every couple of months to aid digestion. There are several materials you can use:

- Crushed oyster shell
- Non-medicated chick starter (crushed)
- Calcium
- Pulverized egg shells
- Garden soil
- Vermiculite
- Sand
  Sand tends to compact the bedding. Use it sparingly.

Moisture

Worms need 75 to 85 percent moisture in their bedding. Mix the dry materials together, then sprinkle them with water and continue mixing and adding water until the mixture feels like a wrung-out sponge (when you squeeze it in the palm of your hand, only a few drops come out).

Photo by Sam Angima, © Oregon State University.

Figure 13. Always keep a 2-inch layer of fresh bedding over the worms and food in your bin.

Maintenance

Always keep a 2-inch layer of fresh bedding over the worms and food in your bin (figure 13). Add fresh bedding as needed depending on the season and the activity of your worms, as the old bedding is consumed, or whenever odors or fruit flies become a problem. Do not cover air vents or holes with bedding.

Keep bedding as moist as a wrung-out sponge. In a plastic bin, mix in dry bedding to absorb excess moisture. You may need to add water more often to wooden bins to keep the contents moist.

Food

How do I feed the worms?

Add additional food scraps to the new worm bin gradually at first. Introduce about ¼ to ½ a pound of food scraps per pound of worms per week until the worms become accustomed to their new diet. If you maintain a temperature of 55 to 77°F around your worm bin, you can gradually increase food amounts as the worms multiply.

Pocket feeding

Pull aside some bedding, and make a hole where you can put food scraps. Cover the scraps with the bedding to help reduce fruit flies and odors. Choose a different spot each time you bury the food scraps to encourage worm distribution throughout the bin.

Surface feeding

Spread food scraps in a thin layer (no more than 1¼ inches deep) on top of the bedding layer and add more fluffed-up bedding on top. The worms move upward toward the new food as they finish the old food. This makes harvesting the compost easier because most of the worms are in the uppermost layer of food and bedding. As worms burrow up through the deeper layers, their trails help circulate oxygen, which reduces odors.

If by chance you overfeed your worms, stop feeding and wait up to 2 weeks before feeding again. You'll know you have overfed your worms if you find untouched food 2 to 3 weeks after you've added it. Observation is the key to success in vermicomposting!

Photo by Sam Angima, © Oregon State University.

Figure 14. In this finished vermicast, you can see that the worms did not consume the potato peels. Whenever possible, avoid putting potato peels in the worm bin. They contribute to anaerobic conditions in the bin. (The greenish material is colored paper towel, which worms do consume.)

What should I feed them?

Red wiggler worms have amazing powers of digestion and will consume just about any organic matter you put in the worm bin. The following types of food are acceptable for feeding worms. Note: Chopping food items into small pieces (½ to 1 inch or smaller) ensures faster breakdown by microorganisms.

- **Fruit and vegetable scraps and peels.** Potatoes peels are okay, but worms tend to avoid them (figure 14).
- **Eggshells or other source of grit** (see page 8). These should be ground or pulverized.
- **Coffee grounds, filters, and tea bags with staples removed.** You can mix them into the worm bin at any time.
- **Plain cereal, bread, and pasta.** Use small amounts only, as they tend to clump up. Be sure to wet them first.
- **Dryer lint (natural fibers only, such as cotton, linen, or wool).** Lint provides the “fabric” for air circulation.

Food items that are NOT acceptable

Though your worms will eat just about any organic matter, some types of food may entice undesirable insects and animals to live in the worm bin, too. The foods in the list below are not appropriate to feed the worms because they attract pests, can be toxic to worms, or create unpleasant odors.

- **Meat, poultry, or fish (bones, skin, or drippings).** These develop odors and easily attract other pests.
- **Oils (such as butter, salad dressing, or mayonnaise).** These smother worms (they breathe through their skin).
- **Dairy products.** These products may cause anaerobic conditions and odors.
- **Highly acidic or spicy foods, such as citrus (especially peels) or onions.** These may produce acidic conditions and may be toxic to worms.
- **Pet feces.** Feces can contain large quantities of pests that are not beneficial to worms or to the final compost product.

The guideline for vermicomposting is: **When in doubt, leave it out!**

Harvesting the Compost

When should I harvest my vermicompost?

Vermicompost or vermicast is a mixture of worm castings and decomposed organic matter (figure 15). It can be very wet at harvest time depending on the kitchen waste you use (for example, lots of banana and fruit peels). If you wish to use a sieve to make debris-free compost, then allow the vermicast to dry first.

Photo by Sam Angima, © Oregon State University.

Figure 15. Vermicast is a mixture of worm castings and decomposed organic matter.

It generally takes about 3 to 6 months from initial bin setup to finished worm compost. It is ready to harvest if it looks like crumbly chocolate cake and smells earthy and fresh.

Can I touch worms with my bare hands?

It is okay to touch and handle worms with your bare hands as you work with them. Remember that they are photophobic (sensitive to light), so they will tend to move away from you as you add new food waste and new bedding, or when you harvest the vermicast. If you are not fond of touching worms, latex or vinyl gloves are appropriate to use. Be sure to wash your hands thoroughly with soap after handling worms or worm bins.

How do I harvest my vermicompost?

Harvesting involves removing the finished compost from the bin and separating it from the worms. After several months, worms need to be separated from their castings. At high concentrations, the castings create an unhealthy environment for them. To keep your worms healthy, harvest at least twice a year.

There are several methods to separate worms from the compost. Some worms are lost in the process, but there should be enough worms saved to restock the bin. (If you don't separate out the worms, you can still use the compost in the normal way. But, the worms in it will eventually die.)

Whichever method you choose, the compost you harvest will probably contain a worm or two, along with old food scraps and bedding. This is fine. If you use the compost outdoors, then (depending on moisture, temperature, and the composition of the soil) some worms might survive. If you use the compost for your indoor plants, it is best to remove all the worms. Conditions in pots are not beneficial for worms.

Dump and sort

(This is by far the most recommended method.)

Lay out a tarp in the sun or under a bright light (figure 16). Divide the contents of the bin into small, cone-shape piles on the tarp. Wait 20 minutes. (You can use this time to clean bins and add fresh bedding.) The worms will move away from the light and into the center of each pile. Brush the compost off the top of each pile until most of the worms are in the pile's center. Repeat until all the worms in each pile are at the bottom (figure 17).

Collect the worms and weigh them (you need to know space needs for your next composting project). Then, put them back in their bin with fresh bedding. If you have more worms than you need for your bin, start another worm bin or share your worms with someone else.

Bait and switch

(This method only works with large bins more than 2 cubic feet in volume.)

Move the worm bin contents to one side of the bin so it fills about ¾ of the bin's volume. Add fresh bedding and food to the empty section. Let the new section stand for 2 to 4 weeks without adding fresh food to the old section.

Photo by Sam Angima, © Oregon State University.

Figure 16. The first step in the "dump and sort" method for harvesting vermicast. On a tarp in the sun or under a bright light, divide the contents of the bin into small, cone-shape piles.

Photo by Bill Biernacki. Used by permission.

Figure 17. The pile on the right shows the last step in the "dump and sort" method, in which only the worms remain. The pile on the left has not been harvested.

Water and cover only the new side of the bin. The light and lack of moisture will cause the old side to dry out and speed up worm migration. As it dries out, the worms will leave it for the new side. After the worms have moved, harvest the old section as vermicompost.

Plan to not feed your worms for at least 2 weeks before starting this harvest method. That way, you can harvest much sooner.

Scoop and return

Simply take out the top third of the bin, which is comprised mainly of bedding, worms, and undigested food scraps. Scoop out what is left on the bottom for use in the garden. Return the other contents to the bin, and mix well with fresh bedding.

How should I use my vermicompost?

You can use worm compost straight from the worm bin or store it for later use as a soil amendment or a slow-release fertilizer. To use it as a soil amendment, blend the worm compost with potting soil. Typically, worm compost makes up 25 percent of the total soil volume for container plants. You can also add it to garden soil when planting annuals, perennials, vegetables, trees, and shrubs.

Use it as a fertilizer by lightly topdressing houseplants or spreading 1 to 2 inches around the base of flowers and vegetables. Avoid letting the worm castings come into direct contact with stems or trunks.

Check the worm bin often for leachate. You can safely use diluted leachate (ratio of 10:1 water to leachate) in the garden rather than throwing it away. Fresh leachate is high in beneficial microorganisms.

Finished worm compost contains seeds that went into the worm bin with food scraps (such as cucumber, tomato, and squash). Worms don't digest seeds, nor is the worm bin environment hot enough to kill them. Because the developing vermicast is an ideal place for seeds to sprout, you may get volunteer seedlings (figure 18) where you use your vermicast.

More About Worm Health

What other creatures live in the worm bin?

Many micro- and macroorganisms live with the worms in your healthy bin. Some are beneficial to the composting process and some are worm predators. **Beneficial** microorganisms and invertebrates (animals with no backbones) include:

- Aerobic bacteria
- Fungi and molds (be aware of allergies to spores)
- Enchytraeids (pot worms)
- Millipedes
- Spiders and mites
- Springtails
- Protozoa
- Gnats and their larvae
- Beneficial nematodes

Are there worm pests or diseases I should be concerned about?

Some of the organisms that can harm worms and the vermicompost are:

- **Anaerobic bacteria** caused by poor drainage, especially if holes at the bottom of the bin are clogged. If there is too much moisture in the

Photo by Sam Angima, © Oregon State University.

Figure 18. Because worms don't digest seeds, you may get volunteer seedlings, especially if the bin is left for a while without active feeding (such as when you are preparing to harvest vermicast).

bin, the worms will not consume the food waste, and the bin may smell.

- **Fruit flies.** These indicate that there is too much nitrogen-based material in the mix (such as banana peels, watermelon, and cantaloupe).
- **Slugs and snails.** These come in on bedding material (leaves, grass, etc.).
- **Centipedes.** Remove them. They are predators.
- **Soldier flies (maggots and adults).** They outcompete worms for food.
- **Ants.** This means the bedding is too dry. Moisten it.
- **Mites,** especially the worm mite (a small reddish to brownish mite, visible to the naked eye). High populations of mites may cause worms to stop feeding.
- **Flatworms.** Remove and destroy them.

Troubleshooting Common Worm Bin Problems

Problem	Cause	Solution
Worms dying	Too much food	Reduce the amount of food you add. Increase worm population or add bedding.
	Too wet	Add dry bedding material.
	Too dry	Add water until slightly damp. Add moist bedding if needed.
	Extreme temperatures	Move bin to a place where temperature is between 55° and 77°F. Make sure bedding is adequate.
	Food and bedding all eaten	Harvest compost. Add fresh bedding and food.
Bin attracting ants	Too dry	Moisten bedding
Bin attracting flies	Food exposed	Cover food completely.
	Fruit or high sugar-based food scraps in the bin	Reduce amount of fruit peels or freeze them before adding to bin. Cover bedding with cardboard. Put a small cup filled with vinegar or wine in the bin to attract the flies and drown them. Stop feeding for 2 to 3 weeks.
Rotten odor	Too wet	Make sure drain holes are not blocked or too small.
	Not enough oxygen	Add more holes for airflow.
	Too much food	Cover food with dry bedding, and reduce the amount of food you add.
Bin smells bad/ attracts flies	Too wet; food scraps exposed	Add a 4-inch layer of dry bedding and stop feeding for 2 to 3 weeks.
	Problem materials	Remove meat, dairy, grease, etc.
Rodents in bin	Bin is not rodent resistant	Use traps or baits and a rodent-resistant bin (no holes or gaps larger than ¼ inch).
	Problem materials	Remove meat, dairy, grease, etc.
	Too many fruit and vegetable trimmings	Add a 4-inch layer of bedding, and stop feeding for 2 to 3 weeks.
Sowbugs, beetles in bin	These are good for your worm compost!	This is not uncommon. Sowbugs and beetles coexist with worms.

How do I take care of the worms in the winter?

You can continue worm composting all winter long if your bin is in a place that does not freeze (such as a pantry, laundry room, basement, or heated garage or porch).

Another way to keep your worms alive and active through the winter is to put mature compost from any source in a regular composting bin and add worms to the center. To this compost, add food throughout the winter by digging a hole in the center, putting in the food, and burying it. Worms will congregate in the center where there is food and warmth, and stay active (though not as active as when the weather is warmer). Due to the cold, they will consume food at only about half the rate as in summer months. This method works well in schools where there is no space for a bin in the classroom, and it also helps eliminate fly problems.

Or, you can let your worms rest outside through the winter by burying the bottom half of your bin in the ground and piling straw or leaves around and on top of it for insulation. Don't cover air holes. There is a risk with this method that your worms might die during an uncommonly cold or wet winter.

What if I will be away from home for a while?

If you will be away from home for an extended time (2 to 3 weeks), feed your worms well before you leave. Be sure their bedding is sufficient and that they are protected from temperature and moisture extremes. Worms can survive long periods without fresh food, as long as temperature and moisture conditions are favorable. Note that if they go without food, their reproductive capacities are reduced.

What other resources are available on vermicomposting?

Constructing a Worm Compost Bin (ENRI-312). University of Kentucky Extension Service. http://www.ca.uky.edu/enri/enri312rev.pdf

Earthworm Ecology, 2nd edition. 2005. Edited by Clive Edwards. CRC Press.

Vermicomposting Resources. University of Wisconsin Extension Service. http://www3.uwm.edu/Dept/shwec/publications/cabinet/factsheets/VermicompostingResources.pdf

Worms Eat My Garbage. 1997. Mary Appelhof. Flower Press.

Published October 2011.

University of Idaho Extension

CIS 1215

Anaerobic Digestion Basics

Lide Chen and Howard Neibling

Introduction

Dairy, potatoes, and sugar beets—all important agricultural commodities in Idaho—also generate a huge amount of wastes. Two big waste-related challenges facing the dairy and food processing industries are emissions of odors and gases and manure management. Gas emissions include greenhouse gases; ammonia (NH3), a colorless gas with a pungent smell; and hydrogen sulfide (H2S), a colorless gas with the foul odor of rotten eggs.

Rising energy prices, more restrictive regulatory requirements, and increasing concern over greenhouse gas emissions are causing many people in Idaho's dairy and food-processing industries to consider anaerobic digestion (AD) of wastes from their operations. Anaerobic digestion technology is being viewed as a way to address environmental concerns, generate renewable energy, cut bedding-material costs, reduce pathogens and weed seeds associated with manure, improve manure nutrient availability to plants, and sometimes generate new revenues.

What Is Anaerobic Digestion?

Anaerobic digestion is a series of biological processes that use a diverse population of bacteria to break down organic materials into biogas, primarily methane, and a combination of solid and liquid effluents, the digestate (figure 1). It occurs in the absence of free oxygen.

Organic materials are composed of organic compounds resulting from the remains or decomposition of previously living organisms such as plants and animals and their waste products. Sources of organic material for anaerobic digestion include dairy manure, food processing waste, plant residues, and other organic wastes such as municipal wastewater, food waste, and fats, oils, and grease.

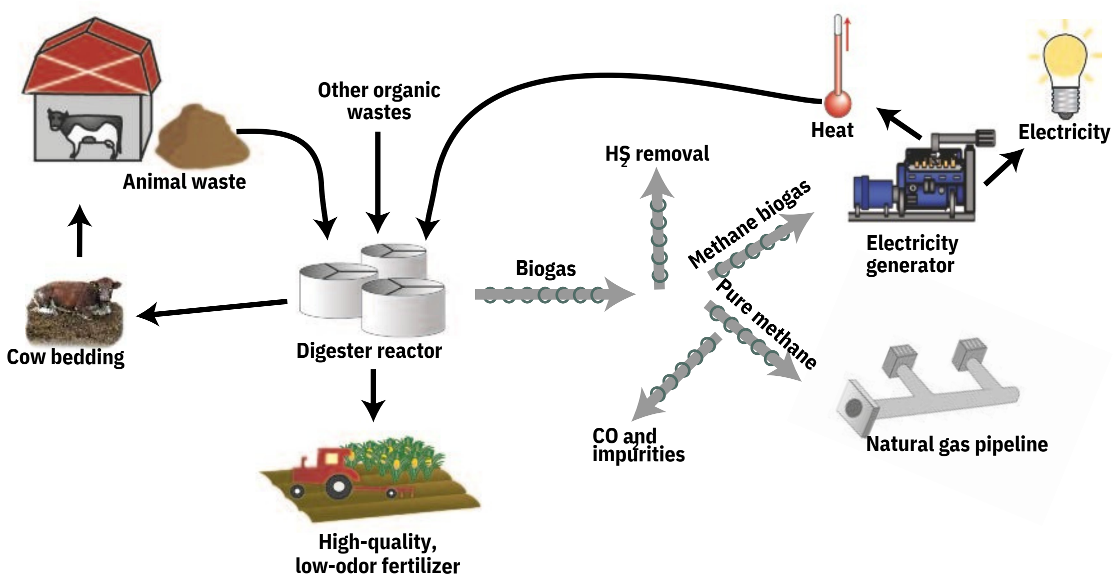

Figure 1. Typical anaerobic digester configurations. (Modified from https://erams.com/AD feasibility. Original prepared by Sarah G. Lupis, Institute for Livestock and the Environment, Colorado State University.)

The end product biogas is composed of methane (CH_4, typically 60–70% by volume) and carbon dioxide (CO_2, typically 30–40% by volume) as well as small amounts of H_2S and other trace gases. Biogas can be combusted to generate electricity and heat or processed into renewable natural gas and transportation fuels.

Separated digested solids can be composted, utilized for dairy bedding, directly applied to croplands, or converted into other products such as potting soil mixes. Digested liquid, which contains fewer pathogens and weed seeds and is rich in crop nutrients, can be used as agricultural fertilizer. Digestion of livestock manure also reduces emissions of greenhouse gases and odors.

Benefits of Anaerobic Digestion

The following benefits are commonly recognized:

• Reducing odor missions, which improves air quality

• Harvesting biogas (mainly the greenhouse gases $CH_4$and CO_2), which reduces greenhouse-gas emissions to the atmosphere

• Protecting water quality by reducing the potential for pathogens associated with manure to enter surface and/or groundwater

• Generating energy (gas, electricity, heat) that can be sold for on-farm or off-farm uses

• Killing weed seeds in manure, which reduces costs of controlling weeds in fields

• Reducing bedding costs by using digested fiber

• Improving manure nutrient availability to plants, reducing fertilizer costs

• Possibly receiving carbon credit payments

• Being a better neighbor.

Four-Step Anaerobic Digestion Process

Anaerobic digestion can be divided into four steps (figure 2).

Step 1. Hydrolysis. The first step, hydrolysis, occurs as extracellular enzymes produced by hydrolytic microorganisms (for example, cellulase, amylase, protease, and lipase) decompose complex organic polymers into simple, soluble monomers. Proteins are broken down into amino acids, lipids into long- and short-chain fatty acids, starch into glucose, and carbohydrates into sugars.

Step 2. Acidogenesis. The small molecules resulting

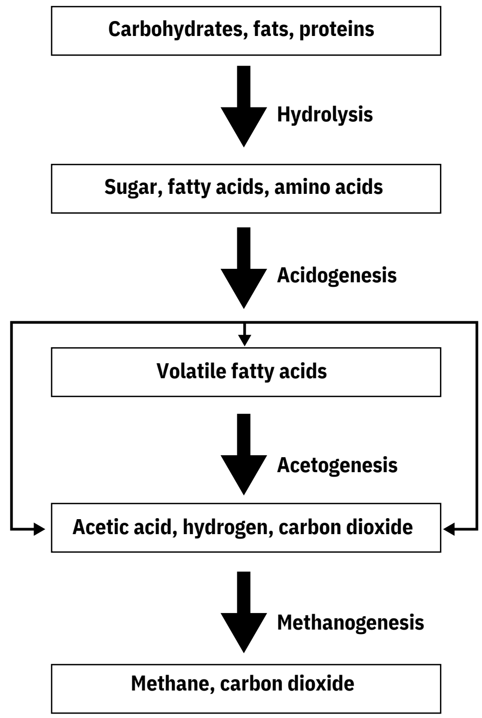

Figure 2. The four-step anaerobic digestion process.

from hydrolysis are converted by acidogens (fermentative bacteria) to a mixture of volatile fatty acids (VFAs) such as acetic, propionic, and butyric acids and other minor products such as hydrogen, carbon dioxide, and acetic acid. Acidogenesis is usually the fastest step in the anaerobic conversion of complex organic matter in liquid-phase digestion.

Step 3. Acetogenesis. In the third step, acetogenic bacteria further convert the volatile fatty acids to acetate, CO_2, and/or hydrogen (H_2).

Step 4. Methanogenesis. Step 3 provides substrates for methanogenesis, the last step in the anaerobic process for methane production.

A stable anaerobic digestion process requires maintaining a balance between several microbial populations. The hydrolysis and acidogenesis steps have the most robust microbes (acid formers), which thrive in the broadest environmental range. They react quickly to increased food availability, so the fatty acid concentration could rise very quickly. The pH range is maintained under normal circumstances by the buffering action of the system provided by CO_2in the form of bicarbonate (HCO^-_3) alkalinity. However, if the acid concentration overcomes the system's buffering capacity, the pH value could be out of the acceptable limits of the acetogenic and methanogenic bacteria (methane formers). When this happens, methane production stops and the acid levels rise to the tolerance level of the acid formers, thus resulting in system failure.

In addition to pH, temperature is a critical factor affecting the balance between these microbial populations. Sudden changes in temperature adversely affect the methane formers, thus affecting the acid formers, too. Any change having an adverse effect on the methane formers increases acid concentration, which in turn reduces the activities of the methane formers.

Feedstocks

Livestock manure and many other substrates including food processing wastes such as cheese whey, yogurt factory wastewater, sugar beet processing wastewater, and fruit and vegetable wastes are commonly used feedstocks.

Feedstock characteristics are important factors affecting biogas production and process stability during anaerobic digestion. The main characteristics of feedstocks include moisture content, total solids (TS), volatile solids (VS) (organic compounds of plant or animal origin that are lost on ignition of the dry solids at 550 °C [1022°F]), particle size, pH, biodegradability, chemical oxygen demand (COD), biological oxygen demand (BOD), and carbon and nitrogen contents. The concentration of volatile fatty acids and NH3, both of which could cause toxicity and process failure at high concentrations, is largely dependent on feedstock characteristics and loading rates.

Table 1 shows the characteristics of lactating dairy cow manure and its biogas potential.

Table 1. Characteristics of lactating dairy cow manure and its biogas potential.

Component	Units	Per cow
Weight	lb/day	150.00
Volume	cubic feet/day	2.40
Moisture	percent	87.00
Total solids	lb/day	20.00
Total volatile solids	lb/day	17.00
Chemical oxygen demand (COD)	lb/day	18.00
Biological oxygen demand (BOD)	lb/day	2.90
Nitrogen	lb/day	0.99
Phosphorous	lb/day	0.17
Potassium	lb/day	0.23
Biogas production[a]	cubic feet/day	47.10
Methane production[b]	cubic feet/day	30.60
Methane (CH_4)[b]	lb/day	1.37
kWh[c]	per day	2.00
Annual kWh		744.00

Source: Liebrand, C. B., and Ling, K. C. 2009. Cooperative approaches for implementation. USDA Rural Development Research Report 217. of dairy manure digesters. http://www.rurdev.usda.gov/supportdocuments/RR217.pdf (accessed November 18, 2013)

[a] 90% of the manure collected; 30% conversion rate of COD to methane

[b] Biogas with 65% methane

[c] 366.6 kWh per 1,000 cubic feet methane

Important Operating Factors Affecting Anaerobic Digestion

Temperature

Two distinct temperature ranges are most suitable for biogas production, and different bacteria operate in each of these ranges. Mesophilic bacteria optimally function in the 90°F to 110°F range. Thermophilic bacteria are most productive in the 120°F to 140°F range. Thermophilic digestion kills more pathogenic bacteria, but the cost to maintain a higher operating temperature is greater. Thermophilic digesters may also be less stable.

Bacterial digestion in covered lagoons at temperatures below 90°F is called psychrophilic. Psychrophilic means a preference for lower temperatures; however, digestion slows down or stops completely below 60°F or 70°F, so these digesters do not produce methane all of the time.

Temperature within the digester is critical, with maximum conversion occurring at approximately 95°F in conventional mesophilic digesters. For each 20°F decrease in temperature, gas production falls by approximately 50%. Even more significant is the need to keep the temperature steady since the methane formers are temperature sensitive.

Hydraulic retention time and loading rate

Hydraulic retention time (HRT), the average time that a given volume of sludge stays in the digester, is one of the most important design parameters affecting the economics of a digester. For a given volume of sludge, a smaller digester (lower capital cost) results in a shorter HRT. This may not be long enough to reach the optimum result such as higher biogas production, lower emissions of odor and greenhouse gases, and higher destruction of chemical oxygen demand, total solids, volatile solids, pathogens, and weed seeds. A HRT range of a few to 40 days is recommended depending on digester type and solids content in feedstocks (table 2).

Table 2. Recommended waste solids content for anaerobic digesters.

Digester type	Solids content (%)	Typical hydraulic retention time (days)	Temperature
Covered lagoon	N/A	30–40	Psychrophilic
Plug flow	11–14	10–25	Mesophilic (68–113°F, optimally around 86 –100°F) or thermophilic (122 – 131°F up to 158°F)
Complete mix	5–10	10–25	Mesophilic or thermophilic
Fixed film	<1	A few days	Mesophilic or thermophilic

Source: www.engr.colostate.edu

Loading rate is the amount of volatile solids fed daily to the digester. Experience indicates that uniform loading, on a daily basis, of feedstocks generally works better.

Co-anaerobic digestion

Animal manure is used as a sole feedstock for most of the digesters currently operating around the world to produce biogas. Although convenient and feasible, using animal manure alone may not represent the most efficient way to produce biogas due to manure's inherent deficiency of carbon (i.e., low carbon/nitrogen ratio if excessive amounts of exposed feedlot manure are in the input stream). Amending dairy manure with other types of organic waste (co-anaerobic digestion) could improve the carbon to nitrogen ratio and biogas production, making the economics of these digesters more favorable.

Anaerobic digestion of more than one substrate in the same digester could establish positive synergisms. The added nutrients could support more microbial growth. During mesophilic co-anaerobic digestion (co-AD) of cattle manure plus fruit and vegetable waste in a continuous stirred tank reactor at 95°F, methane production increased from 230 to 450 ml g-1VS when the fruit/vegetable waste increased from 20% to 50%. Another co-AD of cow manure and organic fractions of municipal solid waste at 131°F with HRTs of 14 to 18 days indicated that adding such waste to the manure significantly increased the methane yield: from 200 ml g-1VS for manure alone to 340 ml g-1VS for the mixture (50% each based on VS).

pH

It should be kept in a range of 6.5 to 7.5. The methane formers are pH sensitive, and pH values outside of the range will affect their metabolic rates and slow or completely stop methane production, resulting in decreased biogas production or digester failure.

Pretreatment

Lignocellulosic biomass, such as agricultural residuals and energy crops (for example, switch grass and Miscanthus), consist mainly of cellulose, hemicelluloses, and lignin. These three compounds render lignocellulosic biomass resistant to biodegradation. Therefore, physical, chemical, or biological pretreatments are preferred.

Safety

Methane (the major component of the biogas generated from anaerobic digestion), when mixed with air, is highly explosive. In addition, biogas is heavier than air, and it displaces oxygen near the ground if it leaks from a digester and accumulates in a nonventilated space. Further, biogas can act as a deadly poison if H2S is present, which occurs most commonly in the biogas from anaerobic digestion of manure. Given these three points, extreme caution is warranted when operating an anaerobic digester.

Types of Anaerobic Digesters for Animal Farms

Covered lagoons

A covered lagoon digester is a large, in-ground, earthen or lined lagoon with a flexible or floating, gas-tight cover (figures 3 and 4). Covered lagoons are used for digester feedstock of 0.5 to 2% solids. They are not heated digesters. Hydraulic retention time is usually 30 to 45 days or longer. They are best used in warmer regions, where atmospheric heat can help maintain digester temperature.

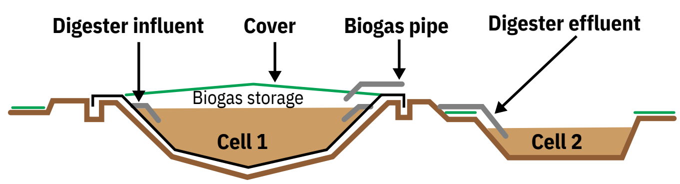

Figure 3. Covere-lagoon schematic. (Source: http://www.epa.gov/agstar/anaerobic/ad101/anaerobic-digesters.html)

Figure 4. Covered-lagoon digester. (Source: http://www.epa.gov/agstar/anaerobic/ad101/anaerobic-digesters.html)

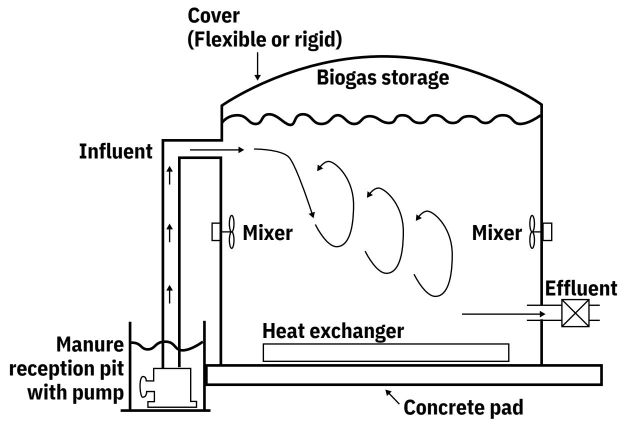

Figure 5. Complete-mix digester schematic (Source: http://www.epa.gov/agstar/anaerobic/ad101/anaerobic-digesters.html)

Figure 6. Complete-mix digester. (Courtesy of Leo Maney, Clear Horizons LLC).

Complete-mix digesters

Complete-mix digesters are either aboveground cylindrical tanks or belowground rectangular pits where manure is mixed (figures 5 and 6). They have either rigid or flexible covers. The operating temperature can be in either the mesophilic or thermophilic range. The complete-mix digester is best suited to process manure with 3 to 10 % solids. HRT ranges from 10 to 25 days.

Plug-flow digesters

A plug-flow digester consists of a cylindrical tank in which the gas and other by-products are pushed out one end by new manure being fed into the other end (figure 7). This design handles feedstock consisting of 11 to 14% solids and typically employs hot-water piping through the tank to maintain the necessary temperature. The plug-flow system accounts for more than 50% of all digesters presently in use in the United States.

A plug-flow digester consists of a long, narrow, insulated and heated tank, which is built partially or

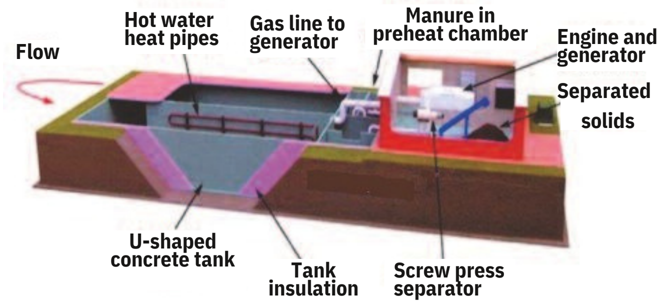

Figure 7. Plug-flow digester schematic. (Source: Jerry Bingold, Innovation Center for U.S. Dairy).

fully below the ground, with a rigid or flexible cover. It is usually operated in the mesophilic temperature range. It is most appropriate for livestock operations that remove manure mechanically rather than wash it out. Manure is added each day at one end of the digester and is decomposed as it moves through the system as a "plug." After a 15- to 30-day HRT, the plug of manure will reach the outlet of the digester.

Fixed-film digester

A fixed-film digester is essentially a column packed with media, such as wood chips or small plastic rings, that supports a thin film of bacteria called a biofilm (figures 8 and 9). Methane-forming microorganisms grow on the media.

This design handles feedstock containing 1 to 2% solids and uses a shorter retention time, as short as 2 to 6 days. The short HRT allows the use of relatively small digesters compared with other digester options for a given volume of influent. Usually, effluent containing less than 1% solids is recycled to maintain a constant upward flow.

One drawback to fixed-film digesters is that manure solids can plug the media. Removing manure solids from these digesters reduces potential biogas production.

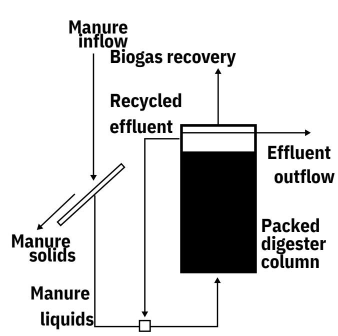

Figure 8. Fixed-film digester schematic. (Source: http://www.extension.org/pages/30307/types-of-anaerobic-digesters).

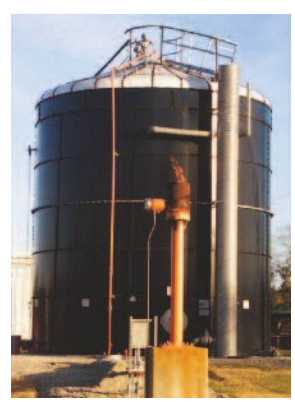

Figure 9. Fixed-film digester. (Courtesy of Ann Wilkie, University of Florida—IFAS).

Anaerobic Digestion Technology Selection

Different types of anaerobic digesters may be appropriate for a specific animal farm depending on its manure-handling methods. Selection of anaerobic digester type is also highly dependent on solids content (table 2).

A number of hybrid systems are being designed and installed. This is a strong indication that no single system is right for all situations. For Idaho dairies, the plug-flow and complete-mix digesters appear to be suitable types.

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Additional Resources

Publications

Balsam, J. 2006. Anaerobic Digestion of Animal Wastes: Factors to Consider. National Center for Appropriate Technology. Available on the Web at: https://attra.ncat.org/attra-pub/summaries/summary.php?pub=307

Barker, J. C. 2001. Methane Fuel Gas from Livestock Wastes: A Summary. Publication #EBAE 071-80. North Carolina State University Cooperative Extension Service, Raleigh, NC.

Callaghan, F. J.,Wase, D. A. J., Thayanithy, K., and Forster, C. F. 2002. Continuous Co-digestion of Cattle Slurry with Fruit and Vegetable Wastes and Chicken Manure. Biomass Bioenergy 27(1): 71–77.

Hartmann, H., and Ahring, B K. 2005. Anaerobic Digestion of the Organic Fraction of Municipal Solid Waste: Influence of Co-digestion with Manure. Water Res. 39(8): 1543-1552.

Websites

United States Environmental Protection Agency (http://www.epa.gov/agstar/anaerobic/)

eXtension (http://www.extension.org/pages/30307/types-of-anaerobic-digesters)

Penn State Extension (http://extension.psu.edu/natural-resources/energy/waste-to-energy/resources/biogas)

Cornell University (http://www.manuremanagement.cornell.edu/Pages/Topics/Anaerobic_Digestion.html)

Colorado State University (http://www.engr.colostate.edu/~jlabadie/Decision%20Tree/intro.cfm)

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ILLINOIS ENVIRONMENTAL PROTECTION AGENCY

Visit our website to see what can be recycled in your curbside bin and to use our tool to find a recycling location near you! Link below.

Recycle Right

Putting non-recyclables or contaminated items in your bin can result in an entire batch of recyclables being thrown away. See what can and can't be put in your curbside bin on our website.

Remember

Recycling works best when coupled with reducing and reusing resources. Buying recycled products also contributes to recycling program success!

RECYCLE

https://www2.illinois.gov/epa/topics/waste-management/Pages/recycling.aspx

Take a Breath of Fresh Air

Recycling one ton of paper saves enough energy to power a home for 6 months, saves 7,000 gallons of water, or reduces greenhouse gas emissions by one metric ton, not to mention saves some trees!

Support Jobs

Recycling has accounted for 757,000 jobs, $36.6 billion in wages, and $6.7 billion in tax revenue. For every 1,000 tons of materials recycled 1.57 jobs are supported!

Get Your Money's Worth

More than $700 million worth of aluminum cans are thrown away each year. Recycling these cans could put money in your pocket!

Sources: US EPA, Aluminum Association

RECYCLING GUIDELINES

YES!

Clean & Empty

Replace lids & caps

METAL
Steel & Aluminum Containers and Foil

PAPER
Cardboard (flattened),
Office Paper, Newspaper, Magazines

CARTONS
May be acceptable in some programs, check with local authority.

GLASS
Containers: Bottles & Jars Only

PLASTIC
Containers: Bottles, Tubs, Jugs, and Jars Only

NO!

Put material in loose - Not in Bags

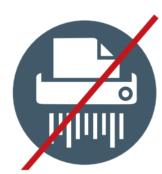
No Plastic Bags
No Plastic Wrap
(return clean to retailer)

No Big Items (Electronics, Wood, Propane Tanks, Scrap Metal or Styrofoam – check local authority for other options)

No Tanglers (Hangers, Hoses, Wire, Cords, Ropes or Chains)

No Clothing
Textiles or Shoes (donate)

No Food, Liquid, Diapers, Batteries or Needles



No Shredded Paper
(check with local authority for other recycling options)

These Guidelines represent the common items accepted in most recycling programs in Illinois. For greater detail on specific items or programmatic variations, reach out to your local authority.

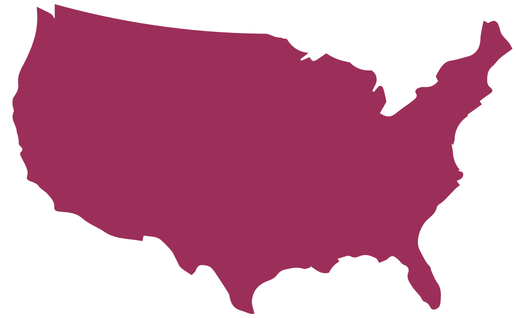
For more detail, see the IEPA online resource at
https://www2.illinois.gov/epa/topics/waste-management/Pages/recycling.aspx

ILLINOIS ENVIRONMENTAL PROTECTION AGENCY

Reuse

The act of using a product again to lengthen its lifespan, whether for its original use or to fulfill a different purpose

Approximately 262 Million tons of Municipal Solid Waste is Generated Annually in the U.S.



That's 4.48 Pounds per Person per Day

Source: U.S. EPA MSW Report (2015)

WHY REUSE?

Reuse keeps items and materials out of the waste stream

Approximately 60% of textiles are landfilled each year. This is clothing that could be donated.

Reuse reduces the strain on valuable natural resources

Twelve trees are used to produce one ton of newspaper and twenty-four trees are used to produce one ton of printing/office paper.

Reuse saves energy and creates less pollution

An energy equivalency of more than 32 million barrels of oil were used to produce the 33 billion liters of bottled water that were consumed in the U.S. in one year

Sources: U.S. EPA SMM Report, Pacific Institute: Energy Implications of Bottled Water, Dartmouth College: Forest and Paper Industry Facts

TIPS FOR REUSE

- Rent tools and equipment or borrow them from your friends, share your own items in return
- Take advantage of second hand stores, shop there yourself or donate your own items
- Find unique ways to reuse plastic bags, try using them as liners for your waste
- Rather than sending all of your paper to the recycling bin, use it as gift wrap or packaging material
- Choose household items that are more durable for reuse such as glass containers rather than plastic containers

Waste Reduction

How You Can Help

Say No to Plastic Bags: purchase or make your own reusable bag and use it while shopping.

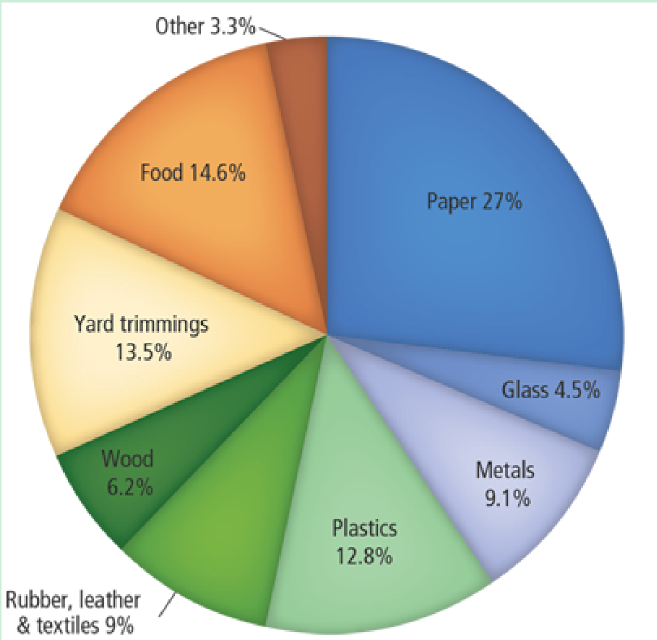
Go Reusable: stop purchasing bottled water and opt for a reusable water bottle, carry it with you wherever you go.

Go Paperless: take steps to stop junk mail, choose paperless billing, think before printing, and purchase recycled paper products.

Ditch Plastics: avoid single use plastics and excessive plastic packaging, look for products that aren't over-packaged, buy from bulk bins, and shop at farmers markets.

Reduce Food Waste: plan ahead and only purchase what is needed, eat leftovers or reinvent them into new meals, compost what you can't eat.

Visualizing Municipal Solid Waste in the U.S.



Source: U.S. EPA Total MSW Generation By Material (2013)

Reducing Waste: If Not You, Then Who?

One of the most important steps we can take to protect our environment is to find ways to minimize the waste we produce. Reducing waste prevents pollution which makes your neighborhood and community a safer and healthier place to live. In the end, you benefit, the environment benefits, and your community benefits.

Take steps to reduce your waste, but remember, the best way to reduce waste is simply to **consume less.**

Illinois Environmental Protection Agency

08.Resources

These resources were compiled using study guides given by NCF-Envirothon, Miami University, University of Ohio, and University of Illinois Extension Offices

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