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The role of U.S. policy in advancing circular economy solutions for wasted food

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ABSTRACT

Food waste is a growing global sustainability challenge. The United States plays a major role in food waste generation and yet has seen limited progress toward significantly reducing the amount of food ultimately being landfilled. Circular economy offers a compelling alternative to the current linear management of food and food waste, but the U.S. also lacks comprehensive public policy that would enable circular economy in the food system. This article provides a systemic analysis of U.S. federal and state policy to identify whether current regulations and initiatives are helping or hindering circular food waste management. One key finding is that the U.S. has ambitious national goals and initiatives aimed at reducing and recovering wasted food, but these efforts are voluntary and lack enforcement mechanisms. Individual states have enacted a wide array of policies expected to both directly and indirectly influence wasted food generation and management, including highly variable requirements for food date labeling and using excess food as animal feed. The majority of U.S. states have policies in place that would support donation of excess food for human use, and a few actually mandate wasted food management through landfill bans or diversion targets. However, the heterogeneity inherent to the observed "patchwork" of state policies is expected to confound broader circular economy goals and potentially limit new business models and stakeholder participation. Therefore, high priorities for policy efforts include federal standardization of date labeling and regional harmonization of state rescue and redistribution policies to support efficient business implementation and compliance.

1. Introduction

Food production and consumption systems currently function within an unsustainable linear model. Immense energy, water, and natural resources (Cuéllar and Webber, 2010; Heller and Keoleian, 2015; Kummu et al., 2012) are consumed to grow and harvest crops, feed livestock, and process and package foods for consumption. Yet up to 40% of this food is never consumed (ReFed, 2016), and its economic value (Buzby and Hyman, 2012) and nutritional content (Spiker et al., 2017) are ultimately lost. In the U.S. alone, 125–160 billion pounds (57–73 million tonnes) of food are lost or wasted each year, due to agricultural overproduction, manufacturing inefficiencies, excess retail supply, and household overconsumption and mismanagement (Gunders and Bloom, 2017). Only about 25% of wasted food streams are being recovered or recycled in the U.S. (U.S. EPA, 2020e), while the majority of food waste is landfilled, which leads to greenhouse gas emissions (Levis and Barlaz, 2011; Bernstad and la Cour Jansen, 2012) that contribute to growing climate change impacts.

However, wasted food can be transformed for environmental, economic, and social gains, by re-envisioning "waste" as a resource through the lens of bioeconomy and circular economy. The bioeconomy (BE) aims for economic growth through the use of renewable biological resources to produce value-added products and energy (European Commission, 2020). The circular economy (CE) aims to decouple economic growth from resource extraction and waste generation by designing out waste and retaining value. The integration of these approaches can lead to transformative change rather than business as usual solutions (D'Amato et al., 2017). Here, we focus on CE, which offers a range of wasted food solutions that can be loosely grouped in three categories (Fig. 1): 1) narrowing resource loops by preventing excess production and reducing food loss at the source; 2) slowing resource loops by rescuing high-quality surplus food, thus retaining its nutritional value; and 3) closing resource loops by recovering the energy, water, and nutrients contained in food waste for value-added use in other

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applications. Further integration of the bioeconomy perspective may foster novel solutions like biorefineries, wherein wasted food serves as a feedstock for new processes that create bio-based energy, fuels, commodity chemicals, and other value-added products (e.g., Dahiya et al., 2018, Hegde et al., 2018; Sharma et al., 2021; Zabaniotou and Kamterou, 2019; Brandão et al., 2021).

Transforming food systems towards circularity is challenging, and many initiatives have not succeeded due to the economic, social, policy, and technology complexity inherent to these systems (NASEM, 2020). Implementing food waste reduction and recycling relies on significant commitment, coordination, and communication among disparate stakeholders (Halloran et al., 2014), as well as new business models and incentive structures (Borrello et al., 2017). Neither are likely to be realized without effective policy interventions that translate sustainable innovations into practice (Kahupi et al., 2021) and provide consistent and effective incentive structures (Leipold and Petit-Boix, 2018; D'Amato et al., 2017). For example, policies may provide liability protection for companies who donate useable food (Evans and Nagele, 2018), financial incentives for firms to convert organic wastes to bio-products (De Clercq et al., 2017), or capital grants to reduce upfront costs of food waste infrastructure investments (Shahid and Hittinger, 2021).

Despite the importance of policy to catalyze CE solutions for wasted food, implementation is limited and widely varied. At the global scale, United Nations Sustainable Development Goals address circularity of food, including increasing agricultural productivity and sustainable agriculture (Goal 2) and halving retail and consumer sources of food waste by 2030 (Goal 12.3) (United Nations, 2015). While these goals provide a framework for countries to align sustainability efforts, they have no enforcement mechanism. At a regional level, the European Union (EU) is addressing food waste within its CE Action Plan as part of a larger effort to achieve carbon neutrality by 2050, along with efforts to reduce food waste generation and increase sustainable food distribution and consumption (European Commission, 2020). A varied policy landscape is seen across countries, including China's efforts to reduce production loss and enhance supply chain efficiencies (Joshi and Visvanathan, 2019), pay-as-you-throw systems for household food waste and landfill and incineration bans in South Korea (Richa and Ryen, 2018), and laws in Italy and France that aim to prevent food waste and divert surplus to feed people (Mourad, 2016).

In the U.S., however, policy has not kept pace with this growing challenge. Globally, the U.S. is the third highest generator of wasted food (behind China and India) (Thi et al., 2015), producing over 60 million tonnes annually, with less than 30% recovered into any value retention pathway (U.S. EPA, 2020c). The lost value of this wasted food represents 2% of the U.S. gross domestic product (Refed, 2022), and typical management by landfilling leads to 170 million MT CO_2-eq annually (3–4% of total U.S. greenhouse gas emissions), which is equivalent to the emissions of 42 coal-fired power plants (U.S. EPA, 2021; 2022; Refed, 2022). The U.S. has an ambitious stated national goal to cut total food loss and waste in half by 2030 (from 218.9 to 104.9 pounds per person based on 2010 data) (U.S. EPA, 2020b). However, the U.S. lacks federal regulations that directly align with this goal, relying instead on voluntary standards and initiatives led by firms, communities, and non-profits. While many food waste solutions have begun to emerge from the private sector (ReFed, 2021), these efforts are confounded by heterogeneous costs and benefits arising from the minimal development and uneven implementation of federal, state, and local food waste regulations (Sandson and Broad Leib, 2019). A recent policy efficiency analysis of food sustainability efforts ranked the U.S. below Organization for Economic Cooperation and Development (OECD) countries and many non-OECD countries in reducing food waste (Agovino et al., 2018).

Thus, there is a clear need for research that informs the development and implementation of U.S. policy to advance CE solutions for wasted food management. Policy-oriented scholarship in the U.S. has focused on understanding drivers of upstream waste generation and barriers to reduction (Thyberg and Tonjes, 2016), connections between policy and consumer behavior (e.g., Neff et al., 2019; Kavanaugh and Quinlan, 2020), and opportunities to enhance infrastructure systems (Babbitt et al., 2022) and technologies to recover and valorize wasted food (Badgett and Mibrandt, 2021 Levis and Barlaz, 2011). Policy analysis papers have assessed food waste challenges globally or within specific countries and regions (Papargyropoulou et al., 2014; Thyberg and Tonjes, 2016; Liu et al., 2016; Giordano et al., 2020; D'Adamo et al., 2021; Fattibene et al., 2020) and have compared regional policies to ones in the U.S. (e.g., Mourad, 2016). Research has also identified competing policy goals across the food system, such as feeding people versus managing waste (Papargyropoulou et al., 2014) or preventing waste as opposed to treating wasted food (Redlingshöfer et al. (2020). While the grey literature includes reports that compare U.S.-specific policies (e.g., Sandson and Broad Leib, 2019), research has yet to comprehensively compile and analyze U.S. federal and state food waste policies through the lens of circular economy.

Therefore, this paper analyzes the landscape of U.S. federal and state policy to determine if current approaches are likely to help or hinder the adoption of circular economy solutions for wasted food management and to identify opportunities for future policy enhancements. While quantitative analysis of policy outcomes is not yet possible, as the U.S. still grapples with measuring wasted food flows and quantifying impacts associated with policy interventions, this study could provide a foundation on which future work performs such a comparison (similar to studies in other regions, e.g., Caldeira et al., 2019). The analysis also focuses broadly on circular economy strategies but does not engage directly with policy related to bioeconomy, another area that is still underdeveloped in the U.S. However, the framework presented herein could be further expanded to explore policies that specifically address circular bioeconomy. To this end, a policy analysis framework is

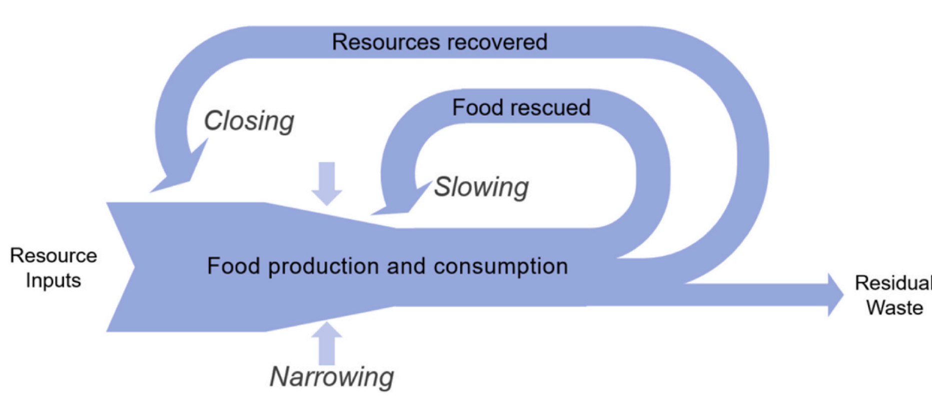

Fig. 1. A circular economy approach to wasted food solutions: narrowing, slowing, and closing resource loops.

developed and applied to first document the current state of policies, then evaluate the extent to which they advance CE practices for wasted food, and finally identify implications and opportunities for future policy development.

2. Overview of U.S. policy mechanisms

Here, we provide a brief overview on U.S. policies, following nomenclature used by U.S. Environmental Protection Agency (U.S. EPA) and U.S. Department of Agriculture (USDA), which classify policies as *regulatory* or *voluntary* (USDA, 2020; U.S. EPA, 2020d; OTA, 1992). Regulatory policies are those mandated by the governing body to benefit or protect society by controlling the behavior of targeted stakeholders or organizations (Lowi, 1972). In this approach, which has been widely used in the U.S. since the 1970s, a government agency establishes prescriptive physical or technology standards and/or mandates or prohibits specific actions (U.S. EPA, 2020d; Hoffman, 2000) and then applies penalties to enforce the required action (Fullerton and Wu, 1998). Regulatory policy instruments create more certainty for businesses and provide lower political risk, but create barriers to entry for competitors and can lead to greater costs passed on to the consumer (Keohane et al., 2000). In the case of food systems, an example of a regulatory approach is banning the disposal of organic waste in landfills. More recently, the U.S. EPA shifted toward voluntary mechanisms of environmental protection, including pollution prevention, product stewardship, and green design, to encourage firms to address pollution costs with their strategic planning processes (Hoffman, 2000). Voluntary approaches attempt to change behavior by using decision-oriented information or changing market signals (e.g., Redlingshöfer et al., 2020; Hoffman, 2000). In the case of climate policy, market-based instruments are considered more efficient and effective in reducing greenhouse gas emissions than traditional command and control regulations because they lower the overall cost of compliance for businesses and are more flexible, but other factors such as political ideologies and constituent pressures play a role in policy adoption (Metcalf, 2009; Keohane et al., 2000). A voluntary approach to food waste might involve a tax on landfilling organic waste, which may encourage food waste generators to seek alternatives.

Both approaches are implemented through a variety of instruments used to achieve the policy goal (Howlett and Ramesch, 1993; Shroff et al., 2012). Policy instruments relevant to wasted food (Table 1) include performance standards, technology standards, market-based mechanisms, education, assistance, information disclosure, bans or prohibitions, or a hybrid of market and performance standards (Hoffman, 2000; Fullerton and Wu, 1998; U.S. EPA, 2020d; USDA, 2022; Sandson and Broad Leib, 2019).

Under regulatory approaches, *performance standards* require a target stakeholder to reduce pollution or emissions, but do not specify how the reduction must be achieved. For food waste, performance standards may include requirements to divert a specified amount of organics from landfill, by donating or recycling excess food. This approach is similar to the original Clean Air Act of 1970, which required manufacturers to reduce emissions of new automobiles 90% by 1975 (Layzer and Rinfret, 2020). On the other hand, a *technology standard* dictates the specific technology that must be used to comply (Hoffman, 2000). For example, the Clean Water Act of 1970 required polluters to adopt 'best available' pollution control technology (Layzer and Rinfret, 2020). *Information disclosure* is an instrument that requires a company to report information that consumers may use to make health and safety decisions, though in some cases (permitting) may also require a fee. *Bans* include prohibiting or phasing out certain chemicals and restricting certain actions, such as the use of landfills as a management pathway for food waste (Fullerton and Wu, 1998; Sandson and Broad Leib, 2019). While not listed in Table 1, *hybrid* instruments may combine both performance standards and market-based instruments.

On the other hand, voluntary or 'suasive' policies (Giordano et al., 2020) encourage behavior changes by making a desired alternative more economically viable or attractive to adopters. Examples of voluntary *performance targets* include non-binding food waste reduction goals, such as the 2015 commitment by the U.S. EPA to halve food loss and waste by 2030 (U.S. EPA, 2020b). *Market-based* instruments like landfill tipping fees, subsidies, or taxes encourage, but do not mandate industries and other stakeholders to change their behaviors, for example, seeking alternate pathways for waste management to avoid higher landfill costs. *Information disclosure* may also have an indirect, voluntary component. For example, companies voluntarily participating in the U.S. Food Recovery Challenge and reporting information on food waste reduction efforts may exert pressure on other stakeholders to participate. *Education* instruments seek to modify behavior changes by providing stakeholders with information about environmental outcomes of decisions or technical knowledge on compliance pathways. Examples include a food waste policy toolkit or sharing resources and best practices on diverting food waste (U.S. EPA, 2020a). *Assistance* instruments provide financial incentives and training to enhance capacity, such as grants to reduce capital costs of new composting or anaerobic digestion infrastructure.

Table 1
Food waste policy instrument classification.

Voluntary		Regulatory	
Instruments	Examples	Instruments	Example
Performance target: diversion goals, emission reduction targets, renewable energy targets, zero waste	Stated goal to divert food from landfill	Performance standard: emissions limit, food waste diversion requirement	State or city regulations specifying a set amount (%) of food waste diverted from landfills
Market-based: financial incentives, subsidies, taxes	Food donation tax incentives and liability protection (civil and criminal)	Technology standard; air or water pollution control systems and technologies	Requiring food waste diversion by a specific technology pathway (e.g., composting) or barring the use of a specific technology
Education: information, resources, guidance, eco-label, date labelling	Training program for workers responsible for separating food waste	Information disclosure: registration, permitting	Requiring permit or registration for composting facilities or a food processor to publish emissions of specified pollutants
Assistance: technical assistance, grants, training	Grants to purchase food waste treatment equipment; technology transfer initiatives	Ban or prohibition - explicitly forbids an action	Landfill ban on food and organic waste

Source: Hoffman, 2000; Fullerton and Wu, 1998; U.S. EPA, 2020d; USDA, 2020; Sandson and Broad Leib, 2019.

3. Methods

This paper aims to identify how key U.S. state and federal food waste policies facilitate or limit circular economy solutions for wasted food. The overall approach was to 1) create a policy analysis framework using models from food waste and circular economy policy literature, 2) collect data for this framework using content analysis of policy documentation, and 3) apply the framework to analyze federal and state policies that may influence generation or management of wasted food in a circular economy context. Each of these steps is described further below.

3.1. Policy analysis framework

Using the policy types and instruments noted in Table 1, a framework was developed by identifying elements found in related policy studies (such as the EU Fusion Project; Vittuari et al., 2016; Caldeira et al., 2019; Giordano et al., 2020) and adapting these for the case of circular economy for wasted food management in the U.S. This analysis also integrates a typology of federal policies (Lowi, 1972; Brenkert-Smith and Champ, 2013) that aligns with how environmental policies are typically classified in the U.S. (USDA, 2020; and U.S. EPA, 2020d) and is set in the context of the circular economy resource loops.

First, the framework organized policies by the scale at which they apply (federal, state, and a few cases of municipal or local laws), as this distinction can play a critical role in policy effectiveness (Mourad, 2016). Next, the framework identifies the typology of policy instrument used and its primary objective (following Caldeira et al., 2019). Next, policies were characterized according to their targets and expected wasted food outcomes. Policy targets are the stakeholders within the food supply chain who are directly responsible for compliance or action under the stated policy aims. The policy outcome is the anticipated impact on wasted food minimization or management. In some cases, there was a direct connection between the target (e.g., a food retailer) and the food waste outcome (e.g., requirement to source separate and divert wasted food from landfill). In other cases, this connection was indirect, as seen for policies aimed at food manufacturers or food health, safety, and nutrition, which may have a secondary impact to wasted food at a different point in the food system (Thyberg and Tonjes, 2016). For example, a food date labeling regulation would compel compliance by manufacturers and retailers, but the ultimate outcome might be a consumer's decision of whether to discard a product according to their understanding of information on that label.

Finally, the framework used an evaluative criteria (Giordano et al., 2020) to assess possible outcomes of the policy on circular economy goals: will the policy or the design of its components likely enable stakeholders to narrow, slow, or close resource loops (Fig. 1), or will it potentially hinder CE goals by unintentionally increasing food loss and waste. This approach departs somewhat from studies that analyze and categorize food waste policies according to the food recovery hierarchy (Mourad, 2016; Papargyropoulou et al., 2014; Giordano et al., 2020); instead evaluating if and how each policy enables circular economy goals. Because the U.S. lags other regions in data collection and stakeholder collaboration efforts, this analysis is unable to quantify policy efficacy (Caldeira et al., 2019; Agovino et al., 2018) or performance relative to global sustainability goals (D'Adamo et al., 2021), but the approach can be extended as more information becomes available in the future.

3.2. Data collection

To identify policies, we followed a similar approach to Fattibene et al., 2020 and compiled U.S.-focused food waste articles (including Redlingshöfer et al., 2020; Mourad, 2016, Thyberg and Tonjes, 2016; Hebrok and Boks, 2017; Papargyropoulou et al., 2014; Edwards et al. 2015; Evans and Nagele, 2018), policy analyses focused on other regions (Giordano et al., 2020; Lucifero, 2016; Vittuari et al., 2016; Caldeira et al., 2019; Liu et al., 2016), and broader studies of circular economy policy (van den Bergh, 2020; Silva et al., 2016). We also reviewed policies compiled from analyses in the grey literature, including government, industry and nonprofit reports and factsheets (Sandson and Broad Leib, 2019; ICF, 2016; ReFed, 2016; Broad Leib et al., 2016a; Broad Leib et al., 2016b; Industrial Economics, Incorporated, 2017; CHLPI, 2013), online resources (Aubrey, 2019), and key government and industry websites (Natural Resource Defense Council, ReFed, U.S. EPA, USDA, Food and Drug Administration (FDA), and specific state environmental protection agencies). The policies noted in the ReFed policy finder website were last updated February 2022.

To verify the most recent state policies were included, we also used Internet searches for "food waste" or "food waste policy" in combination with the names of each U.S. state. Once a common set of policies was identified, official policy text was obtained from the relevant state or federal websites (e.g., U.S. Federal Register) where the regulation was published. As noted in Table 2, the scope of the analysis consisted of food waste policies in the U.S. at the federal and state scale. During this research, we determined that a small number of local governments are adopting food waste bans and diversion targets prior to or in parallel with state actions. These are discussed but not comprehensively analyzed because of the limited number and scope so far, suggesting a need for future research at that scale.

3.3. Application of the policy analysis framework

Analysis of identified policies was carried out "row-by-row" for each dimension in Table 2. Most dimensions could be directly determined from policy text, but one assessment that required additional consideration was mapping policies on the CE model of narrowing, slowing, and closing resources loops. The following process was used in this determination: *narrowing* strategies do not alter speed of material flows through the system, but result in fewer resources or prevent waste from the start (Bocken et al., 2016). Policies classified in this strategy may influence generation of wasted food; for example, by educating or incentivizing individuals to consume less or to use food more efficiently, thus preventing premature discard and additional resource demand. *Slowing* resource loop strategies aim to retain the nutritional value of food, which included policies that both related to rescue and diversion of high quality food surplus for human use or cascading use of excess food for other nutritive purposes in the food system, including feeding animals. Finally, *closing* resource loops includes policies related to diverting materials from landfill and recovering resources embedded within food waste through approaches such as composting and waste-to-energy conversion.

To determine the anticipated direction of the policy outcome on wasted food production and management (help vs. hinder), we evaluated each against known drivers, enablers, and barriers of wasted food reduction, reuse, and recycling. For example, past work has shown that policies that specify date labeling requirements may hinder food waste reduction efforts because of the potential for consumers to misunderstand the label information (Neff et al., 2019; Hebrok and Boks, 2017). On the other hand, assessments of existing state policies on food and organic waste have established that these enable loop closing by expanding recycling infrastructure (Sandson and Broad Leib, 2019; Industrial Economics, Incorporated, 2017). Because the research ultimately determined that only a limited number of states had policies directly related to food waste management, additional analyses of these state cases were performed to characterize specific details on their implementation, including covered entities, compliance thresholds, and any exemptions.

Table 2
Food waste policy analysis framework.

Dimension	Description
Scale	Level of regulatory authority within the U.S. government: Federal, state, or local (municipal).
Typology	Type of policy instrument (see Table 1)
Policy target and outcome	Intended policy purpose, supply chain target (stakeholders required to comply with the policy), and ultimate impact on food loss or waste (either direct or indirect)
Evaluation	Assessment of if and how policy design and implementation enables or hinders CE strategies for wasted food (narrowing, slowing, or closing resource loops, see Fig. 1)

4. Results and discussion

Results presented here synthesize the key insights gained from evaluating U.S. federal and state policies through the lens of circular economy for wasted food management. The discussion is focused on elaborating potential circular economy outcomes and opportunities across the policy landscape. Additional results taken directly from the policy analysis framework are provided in the Supplemental Information (S.I.) file.

4.1. U.S. Federal policy analysis

At the federal level, three policy initiatives were identified to have a direct goal of reducing or minimizing wasted food and an anticipated outcome of enabling circular economy goals (Table 3, first three rows, and S.I., Table S1). However, the three direct instruments are voluntary rather than regulatory, potentially limiting their expected outcome. For example, the U.S. EPA and USDA 2030 Food Loss and Waste Reduction Goal sets a national target to reduce food loss and waste by 50% by 2030. This effort is complemented by the U.S. EPA Food Recovery Hierarchy, which is an educational instrument that provides stakeholders with a prioritized ranking of management strategies that can be applied to help achieve the Reduction Goal. The U.S. EPA Excess Food Opportunities Map is also an educational instrument, providing an interactive map that identifies the locations and magnitudes of wasted food from industrial, commercial, and institutional sources, which may be useful for designing collection routes or siting recovery infrastructure (U.S. EPA, 2022a).

These policies are all expected to enable CE goals, by supporting food waste prevention (narrowing), encouraging rescue of food for people and animals (slowing), or diverting waste from the landfill and combustion to other pathways (closing). Many efforts are part of cross-agency initiatives, primarily in conjunction with the USDA, which also provides technical, education, and financial assistance, including grants to develop anaerobic digestion facilities, grants for food waste pilots in schools, and training programs for school food service workers, (USDA, 2021). The majority of direct federal policies target commercial and institutional food waste generators. Only a limited number of efforts focus on consumers, and these are primarily educational instruments intended to help consumers reduce waste or compost at home or school (U.S. EPA, 2020a; USDA, 2021). Educational mechanisms are an important part of food waste solutions, but typically are limited to modifying individual behavior rather than targeting systemic changes (Mourad, 2016) and may not consider diverse household demographics and baseline awareness of wasted food (Di Talia et al., 2019). Educational policies have seen limited success because of the challenges of translating knowledge into attitude and behavior change or integrating food waste minimization into daily lives (Hebrok and Boks, 2017).

The review of policies at the federal level identified a broader set of instruments that are only indirectly related to wasted food. These are further detailed in the S.I (see Table S1). with illustrative examples noted here (Table 3). For example, the U.S. FDA and USDA were given authority by Congress to ensure food safety and prevent mislabeling, but have only implemented universal date labeling requirements for a few food items (Harvard Food Law and Policy Clinic, 2016). The U.S. FDA only requires date labels on infant formula, while the USDA requires a pack date on eggs and allows but does not require date labels on other food items, such as meat, poultry, and dairy, as long as the label is truthful and not misleading (Harvard Food Law and Policy Clinic, 2016; USDA, 2021). The USDA allows manufacturers to voluntarily apply date labels to communicate food quality and recommends the phrase “best if used by” (USDA, 2021). The lack of a standardized federal policy on date labeling has resulted in a significant amount of discretion left to the states, which may limit the potential for strategies to reduce wasted food (See Section 3).

Federal instruments related to food donation are expected to enable

Table 3
Summary of federal policies influencing the circularity of food.

Policy & Typology	Target	Outcome	Evaluation
2030 Food Loss and Waste Reduction Goal; Performance target	National goal for food producers, manufacturers, institutions, and businesses to halve food waste and loss (F, M, W, C, I)	Supports reduction and diversion of wasted food by targets, but no enforcement or requirement standards	Enables all circular economy resource loops
Food Recovery Hierarchy; Education	Ranking of methods aimed to prevent and divert wasted food for targets above (F, M, W, C, I)	Supports reduction and diversion of wasted food by targets, but no enforcement or requirement standards	Enables all circular economy resource loops
Excess Food Opportunities Map; Education	Spatial mapping of wasted food to encourage pathways for some generators (M, W, C, I) and recipients (food banks, anaerobic digestion, composting facilities)	See above; does not include consumer and farm generators	Primarily enables slowing and closing loops
Date Label; Information disclosure and ban	Requires food producers to date label some (eggs, infant formula) but not all foods and prohibits label alternation/ misbranding; goal is food safety (F, M)	Confusion about date label meaning may cause consumers to discard food prematurely (R, C, FB)	Hinders narrowing loop
Date Label; Education	Encourage use of streamlined label language to communicate quality and to encourage donation (F, M)	Supports reduction efforts but no enforcement or required standard (R, C, FB)	Enables narrowing and slowing loop
Food Donation and Tax Protection; Market-based	Liability protection and tax incentives for food donors to encourage rescue of surplus food for human consumption (M, W, C)	Donation retains nutritive value of food and reduces waste, but there are eligibility requirements and financial benefits (All)	Enables slowing loop
Food Safety Modernization; Information disclosure	Best animal feeding practices, inspections, and safety plans required for food producers; primary goal is to minimize animal sickness and protect public health (F, M)	Allowing food producers to feed excess food to animals retains nutritive value (F)	Enables slowing loop
Swine Health Protection; Technology standard	Requires producers of feed for swine to heat treat meat and animal by-product scraps; primary goal is to protect swine and public health (F, M)	Allowing food producers to feed treated excess food to animals retains nutritive value (F)	Enables slowing loop
Feeding Ban; Ban, performance standard, education	Prohibit food producers of ruminant animals (cows, goats) to include most mammalian protein	Food producers not allowed to feed wasted food to ruminant animals could result in value loss	Hinders slowing loop; does not eliminate potential for closing loop

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Table 3 (*continued*)

Policy & Typology	Target	Outcome	Evaluation
	in feed; require facility inspection/ education facilities; to protect public and animal health (F, M)		
Farm Bill; Market-based and technical assistance	Grants for food producers, municipalities, and tribes to develop bioenergy and anerobic digestion (F, I)	Facilitates adoption of wasted food valorization pathways by these targets; could be used by other generators	Enables closing loop

Notes: F: Farmers and farm production, M: food manufacturing and processing, W: wholesale and distributors, C: food service, retail, and other consumer facing businesses, I: Institutions (government, education and correctional facilities), R: Residents, FB: Food banks. The first three rows are policies that directly aim to minimize or manage food waste, while the remaining rows are policies that indirectly influence wasted food outcomes. Sources: U.S. EPA (2020b 2022a, 2022b), USDA (2021), Sandson and Broad Leib (2019). Broad Leib et al. (2016a, 2016b), CHLPI (2013), ReFed (2022), Swine Health Protection, 9 CFR § 166 (2017).

slowing of resource loops. For example, the Bill Emerson Good Samaritan Food Donation Act of 1996 and Internal Revenue Service (IRS) (e.g., 1976 Tax Reform Action) regulations provide protections and market incentives for commercial and institutional entities to rescue and donate 'wholesome' food for human use. USDA voluntary guidance also notes that wholesome, unspoiled food can be donated past the "best if used by" date (USDA, 2021). Excess food not used by humans may be fed to animals, and both the USDA and U.S. FDA have enacted performance targets, education, bans, and information disclosure requirements, beyond which most states enact more strict and diverse policies (Broad Leib et al., 2016b). For example, the USDA via the Swine Health Protection Act requires heat treatment to ensure safety of food scraps fed to animals (2017). The U.S. FDA's Ruminant Feeding Ban seeks to prevent the spread of a group of fatal neurological diseases like Bovine Spongiform Encephalopathy by prohibiting the use of mammalian protein in animal feed for all ruminant animals and requiring extensive reporting, labeling, inspection, and processing.

Finally, efforts to close resource loops are most closely connected to voluntary policy instruments used by USDA and U.S. EPA (see Table S1). These include technical assistance, grants, market-based incentives, and education efforts that aim to encourage development of bioenergy feedstocks and expand anaerobic digestion capacity. For example, the U.S. EPA invested $3 million USD in 2020 as grants to expand the capacity for anaerobic digestion as a landfill diversion solution. This agency also developed the AgSTAR program to provide education and technical assistance to food and agricultural stakeholders building new digester projects for biogas recovery. While the majority of these investments focus on manure management, a growing number of digesters are co-processing manure and food wastes from commercial and industrial sources (Pennington, 2021).

There are few data points that can be used to directly evaluate if U.S. Federal policy efforts lead to food waste minimization and management. According to ReFed (2021), the generation of surplus food in the U.S. increased 12% from 2010 to 2019 (from 72 to 80.6 million tons of unsold or unused food). This estimate suggests that we are far from a goal of halving food waste, but a lack of high-resolution data precludes analysis of the extent to which federal policies play a role in helping or hindering progress (Babbitt et al., 2022). However, policies targeting the slowing loop (feeding people) may be more effective, as the amount of donations increased 8% between 2010 and 2019 (ReFed Insights Engine, 2021). The U.S. EPA (2020e) estimates that 29% of wasted food was managed in the slowing pathway, primarily by feeding excess to animals, as well as through donation (7.3 million tons). Another 28% was reported to be managed by loop closing, through processes such as biochemical processing, anaerobic digestion, composting, or land application.

4.2. State policy analysis

The limited progress in meeting the ambitious national food waste and loss goal is perhaps not surprising, as the governance of solid waste management in the U.S. is typically passed down to states and municipalities. As a result, states follow varied approaches according to local issues, politics, economics, and regulatory priorities, leading to a "patchwork" of state policies connected directly or indirectly to food waste (Silva et al., 2016; Evans and Nagele, 2018). Results of our analysis show that these state policy components are diverse and sometimes at cross purposes, resulting in outcomes that both enable and hinder circular economy. Fig. 2 provides an overview of the most common policy instruments applied in U.S. states as mapped to the CE strategies of narrowing, slowing, and closing resource loops.

4.2.1. State policies and narrowing resource loops

We found no state policies directly aimed at preventing or reducing food loss or waste. However, many states have date labeling polices (both regulatory and voluntary) expected to indirectly influence wasted food outcomes. These policies (Table 4 and Table S2) are widely varied in formulation, with one or more of the following components: 1) a requirement that certain foods be labeled with a date and an explanatory phrase for that date, such as "sell by" or "use by," 2) a prohibition on selling certain foods past the labeled date, and/or 3) exemption of certain food items from the restriction of sale past a labeled date. In total, 44 states have either a date labeling requirement and/or a restriction on past-date sales. States without any date labeling policies include Idaho, Missouri, Nebraska, New York, South Dakota, and Utah. Most states (42) have a date labeling requirement, while less than half (19) have a policy restricting the sale of a food item past a certain date. Over a third (17) have both a date labeling requirement and a sales restriction for a specific food item.

Because states have authority to implement their own date labeling requirements, with limited guidance from federal policies, there is significant variability in the design and implementation of the policies analyzed. Much of this variability is observed within policy language. For example, Alabama's policy allows for 'open-date' labels that communicate freshness, taste, or quality of food, such as "for full fresh flavor use by" or "for wholesome great taste, serve before date stamped below" (Al Code §80-1-22-0.33, 2000). New Jersey requires "Not to be sold after" or "Sell by," while Massachusetts requires the terms "sell by date" or "best if used by date" (N.J. Admin. Code § 8:21-10.20, 2000; 105 Mass. Code Regs 500.006, 2016). States also vary widely in foods covered by these laws. For example, Massachusetts requires date labeling for perishable food items, which they define as having a shelf life of 60 days or less 105 Mass. Reg.500.003 (2016). Washington defines perishable foods as all beverages and foods but excepts alcohol, frozen food, fresh meat or poultry, fish, and raw agricultural commodities. It appears that some of this variability is driven by major food industries within the states. For example, Florida requires date labels and restricts the sale of shellfish past a certain date, and this industry was responsible for $27.8 billion in sales in Florida in 2016 (Fishwatch, 2022).

Even states located in geographic proximity may regulate similar food products in different ways. For example, Pennsylvania date labeling covers all pasteurized items in retail, restaurants, or schools (3 PA Cons Stat § 5743, 2021). Connecticut requires that milk, cream, yogurt, soft cheese, cream cheese be labeled using the terms "sell by," "last sale date," or "must be sold by" (Conn. Agencies Regs. § 22-133-131, 2005; Conn. Gen. Stat. Ann. § 22-197b, 2006), but does not prohibit past-date sales. On the other hand, New Jersey requires fluid milk and yogurt be marked with a label of "not to be sold after" or "sell by" and prohibits

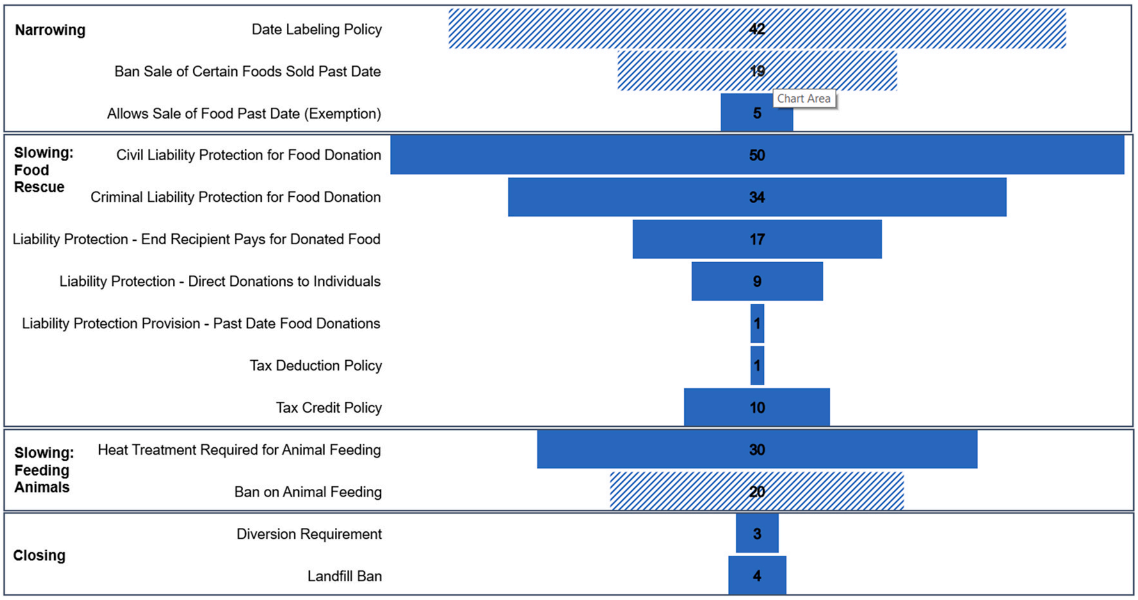

Fig. 2. Summary of state-level policies that are expected to directly or indirectly help (solid bars) or hinder (hashed bars) advancement of circular economy for wasted food. Numbers appearing on each bar reflect the total number of states identified to have each policy component in place. Total for slowing policies (feeding animals) reflects three states that have overlapping policies of both types. Sources: Sandson and Broad Leib (2019), Broad Leib et al. (2016a, 2016b), ReFed (2022).

Table 4
State policies related to date labeling.

Typology	Target	Outcome	Evaluation	
			Variability	Impact
Information disclosure	Require food processors and manufacturers to date label certain food item(s) (M); communicate quality of food to downstream supply chain and end user (W, C, I, FB, R)	Label confusion and diversity of food items covered causes consumer facing businesses and institutions, wholesale, consumers, and food banks to discard food prematurely (W, C, I, FB, R)	High: 42 states 0-4 items covered per state Common food items: milk, shellfish, and eggs	Hinders narrowing loop; may enable slowing (animal feed) and closing loops
Ban	Require food processors and manufacturers to restrict the sale of certain food item(s) past a certain date; communicate food quality to above supply chain targets	Same as above	Moderate: 19 States 0-9 items covered per state Common food items: milk and eggs	Hinders narrowing loop
Ban exemptions	Exempt food processors and manufacturers from ban; allow sale of certain food item(s) past a certain date (M); communicate food quality to above supply chain targets	Provide opportunity for upstream supply chain to reduce premature disposal of certain food items, but the diversity of items covered may reduce potential benefits (W, C, I, FB, R)	Low: 5 states 1 item per state Common food items: milk, packaged bakery, perishable	Enables narrowing and slowing loop to a limited extent

Notes: F: Farmers and farm production, M: food manufacturing and processing, W: wholesale and distributors, C: food service, retail, and other consumer facing businesses, I: Institutions (government, education and correctional facilities), R: Residents, FB: Food banks. Sources: Sandson and Broad Leib (2019), Broad Leib et al. (2016a, 2016b), CHLPI (2013), ReFed (2022), U.S. EPA (2020b), GA. Comp. R & Regs. 40-7-1-.02 (2001).

sales after label date (NJ Rev Stat § 24:10-57.23, 2021; N.J. Admin. Code § 8:21-10.20, 2000). Further, many states do not explicitly detail all foods regulated, but instead use vague terminology, such as "potentially hazardous" foods, which has no consensus in meaning. Some states use this as a blanket term, while others specify lists of food considered potentially hazardous in the regulation text.

These state date labeling policies are primarily targeted upstream in the food supply chain, on food processors and retailers, with a goal of communicating food quality or safety to consumers. However, the expected outcome is that such policies will hinder efforts to narrow resource loops and ultimately lead to downstream increases in wasted food, due to businesses seeking to optimize the taste and experience of their products and consumer confusion about the meaning and differences among labels (Kosa et al., 2007; Pearson et al., 2013; Broad Leib et al., 2016c). In a survey of U.S. consumers, 84% of respondents indicated they would occasionally discard a food product close to the date labeled on the package, particularly if they think the label communicates a message of safety (Neff et al., 2019). Rescue and redistribution of food surplus may also be limited by consumers' concerns about food safety and business concerns about liability (Guillier et al., 2016; Evans and Nagele, 2018).

The variability in labeling requirements also presents a challenge for circular business models, as food manufacturers and retailers are forced to comply with varied regulations within regions or even neighboring states. In 2017, food trade associations (Grocery Manufacturing Association and Food Marketing Institute) attempted to establish voluntary policies to reduce confusion and streamline the labeling process, motivated by the cost of early disposal of food, estimated at $161 billion per year (Aubrey, 2019; Charles, 2017). Currently, Massachusetts appears to be the only state aligned with the new industry standards (Table S2). The lag time and misalignment between industry efforts and policy changes at the state level (and the lack of a unifying federal policy) will continue to challenge efforts to narrow and slow resource loops. Thus, concurrent education policy instruments are also needed to raise awareness and ensure there is a shared understanding of the meaning of label phrases (Hebrok and Boks, 2017). ReFed suggests that standardizing date labeling policies and education awareness campaigns for consumers have the greatest economic return per ton of wasted food avoided, with potential to reduce 398,000 and 584,000 tons respectively (ReFed, 2016).

4.2.2. State policies and slowing resource loops

The policy analysis identified two broad categories of state policies related to pathways that may extend the use and nutritional value of food. In this section we focus first on market-based voluntary policy instruments aimed at enabling commercial entities, institutions, and individuals to rescue and donate food surplus for human consumption. Next, we examine the regulatory policies (performance standards and prohibitions) aimed at downstream supply chain and safety of using excess food to feed animals.

4.2.2.1. Rescue and redistribution of excess food. Two market-based policy instruments were identified to influence extended human use of surplus food as a means of slowing resource loops and retaining value: liability protection and tax incentives. In both cases, the policies' primary purposes are aligned with social aims to increase health and well-being through greater food access, while at the same time protecting public health and business interests. Thus, the reduction and diversion of excess and wasted food is a potential indirect benefit, but not the sole purpose of the laws.

All 50 states have enacted civil liability protections, in addition to civil and criminal protections at the federal level (Table S3). Some states have added liability protection provisions. New Hampshire, for example, includes civil and criminal liability protection, liability protection for donors to allow the end recipient to pay for donated food to cover handling costs, and liability protection for donors who directly donate to individuals (not just to other entities). Massachusetts has a similarly expansive set of protections, and is the only state that explicitly includes liability protection for donations of past-date foods, which enables CE goals of both narrowing and slowing resource loops. On the other extreme, nine states (Illinois, Indiana, Maine, Maryland, Mississippi, Ohio, Virginia, Wisconsin, and Wyoming) do not provide any additional liability provisions.

Further, 34 states have enacted additional provisions that protect donors from criminal liability (Fig. 3). Of these states, 38% (13) include an additional provision to protect the donor from liability when the end recipient pays for donated food, and 12% (4) provide additional liability coverage when donors directly give food to individuals, which extends beyond federal liability protections that only apply when food is distributed for free and/or goes through a nonprofit food recovery intermediary (CHLPI, 2013, Broad Leib et al., 2016a). Of the 16 states that do not provide any additional criminal liability, four extend liability when the end recipient pays for the donated food, five states extend liability so donors can directly donate to individuals, and one (Massachusetts) provides additional liability protection for past-date donations.

States also use tax deductions and credits as a market-based instrument to encourage commercial entities or institutions to donate unused edible food. In total, 11 states have a tax incentive policy, including one (Arizona) that provides a tax deduction and 10 (California, Colorado, Iowa, Kentucky, New York, Oregon, Missouri, South Carolina, Virginia) with tax credits. Market-based incentives are critical, as donors and food banks face significant expenses to store, transport, and handle food and to ensure that donated food complies with government regulations. States can provide financial incentives by additional tax credits or deductions to help low profit-margin stakeholders, such as farmers and small businesses, and extend tax credits/deductions to organizations that partner with recipients who can help defray the cost of food recovery (Broad Leib et al., 2016a).

Some of the enhanced state level liability protections may be related to state-specific aspects of wasted food generation. According to the U.S. EPA Excess Food Opportunities Map (2022), California has the highest amount of food waste generated and has a tax credit and provisions for additional criminal, civil, and direct donation liability protection. Other states with high food waste generation from commercial sectors (such as Florida and Texas) may be able to increase recovery by adding additional liability protections and/or tax incentives to encourage donation. These efforts can be enhanced by education mechanisms or technical assistance to help donors understand their protections under state and federal laws, standardized state and local health department regulations related to donations, expanded collection infrastructure and coordination among stakeholders, and new platforms for sharing decision-relevant data on food quality and availability (Göbel et al., 2015;

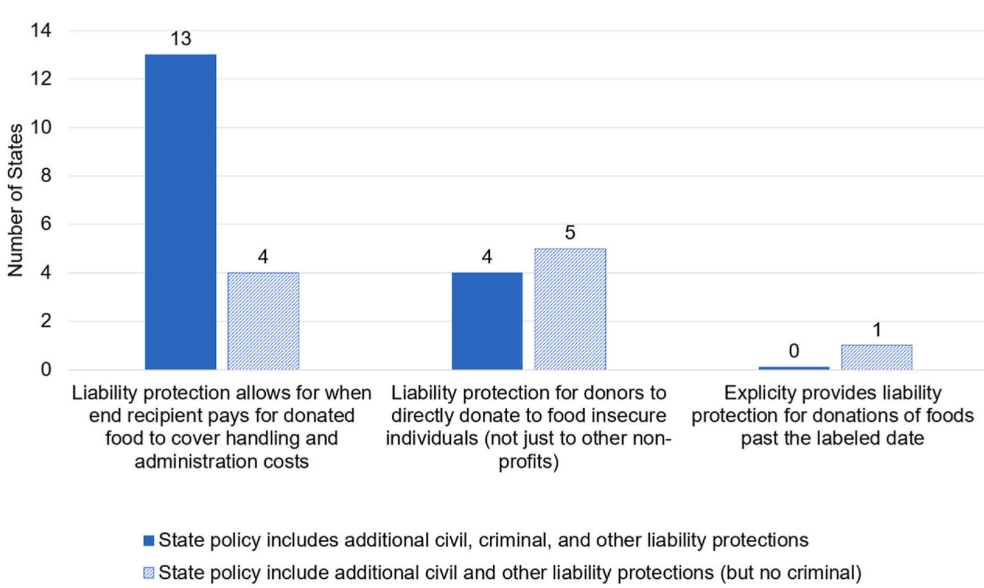

Fig. 3. Disaggregation of the states that have or do not have provisions for additional criminal liability protection. Additional liability protection policy provisions (market-based policy instruments) may enable slowing of resource loops. Sources: Sandson and Broad Leib (2019), Broad Leib et al. (2016a, 2016b), CHLPI (2013), ReFed (2022), U.S. EPA (2020b), AZ. Rev. Stat. Ann. § 42–5074 (1996), AZ. Rev. Stat. Ann. § 43-1025 (2016), MD Cts & Jud Pro Code § 5–634 (2013), MD Health-Gen Code § 21-322 (2013), N.Y. Agric. & Mkts. Law § 71-y-z (2014).

Sedlmeier et al., 2019). Successful implementation will also require internal coordination within a business and external coordination with the food supply chain, which depends on other factors, such as the cost implications of reducing food waste and the adoption of technologies to reduce food spoilage (ReFed, 2016).

4.2.2.2. Recovery of excess food for animal feeding. As a secondary option for retaining the nutritional value of food, surplus may also be recovered and redistributed to feed animals. The policy analysis determined that a majority of states have a policy that prohibits feeding untreated food waste to animals but may allow this pathway if the wasted food first undergoes heat treatment or other safety measures (Table 5). As a result, the ultimate outcome for circularity is mixed. We expect increased value retention through resource slowing loops in those states that do not restrict these practices or that allow animal feeding after food materials are treated. Policies prohibiting any excess food (treated or untreated) from being diverted to animal feed will hinder the resource slowing loop but do not preclude the use of downstream valorization processes to close resource loops.

Nineteen states prohibit animal feed pathways for wasted food in any form - treated or untreated. The variability is even greater when considering specific animal feed pathways to which these restrictions apply. For example, only a handful of states (Illinois, Kansas, Nebraska, Maryland, Nevada) apply these policies to all animals, while the majority of states only restrict feeding swine. The increased regulatory attention on swine stems from disease outbreaks during the 1980s, such as foot-and-mouth disease in swine, and bovine spongiform encephalopathy (mad cow disease) in cattle, which have been linked to animal products in livestock feed (Dou et al., 2018; Salemdeeb et al., 2017). As a result, some states have taken a more restrictive stance on these practices (Broad Leib et al., 2016b), leading to geographic heterogeneity, even within a single region. For example, Illinois prohibits feeding animal and vegetable waste to all animals §720 ILCS 5/48-7 (2022), but nearby Indiana only prevents feeding untreated food waste (animal material only) to swine, allowing for feeding after heat treatment (Indiana Code §15-17-10-16, 2015). While New York bans only the feeding of untreated food waste to cattle, poultry, and swine, nearby New Jersey universally bans feeding swine in addition and restricts feeding of unpasteurized dairy products to other farm animals (N.Y. Agric. & Mkts. Law §72-a, 2014; N.J. Rev Stat § 4:4-22, 2020). These inconsistencies are expected to limit the wider use of this diversion pathway, particularly in cases where food waste hauling companies might service multiple adjacent states that have different laws in place.

Table 5
Division of states with policies regulating feeding untreated or any wasted food to animals.

Animal Category	States prohibiting feeding wasted food in any form, *treated or untreated* (Ban)	States requiring treatment of wasted food fed to animals (Technical Standard)
All animals	2	3
Swine and other specified animals (farm animals, domestic, cattle, livestock, or poultry)	1	6
All or some animals except swine	3*	0
Swine only	13	23*
Total states with each policy	19	32

Note: Total in above table does not equal 50, wherein two states (Utah and Alaska) have no policies regulating or prohibiting the feeding of food waste to animals and three states (Iowa, Georgia, and Massachusetts) have both (*prohibiting feeding wasted food in any form to all animals, but swine can be fed wasted food if treated). (Sources: Refed, 2022; N.Y. Agric. & Mkts. Law § 72-a, 76, 2014).

The geographic distribution of food supply chains and production infrastructure in the U.S. may have some influence on the observed policy landscape. For example, Illinois and Iowa rely on exports of grains (wheat, corn, feed grains), valued at \$2.6 and \$3.0 billion, respectively (USDA, 2021). Iowa is also a major exporter of pork, which is valued at \$2.6 billion (USDA, 2021). Both states ban feeding wasted food directly to animals; Iowa, however, has an exception allowing wasted food that has undergone heat treatment to be fed to swine (Refed, 2022). This economic impact is noted in other countries; the high cost of treating food waste in addition to the bans on feeding food waste to swine, chickens, and ruminant animals in the EU and Australia limit the export of meat from Asian countries that allow this practice (Joshi and Visvanathan, 2019). While causal linkages cannot be directly established between U.S. agricultural production and policy formulation, research is needed to assess potential regional economic disincentives for recovering wasted food for animal feed pathways.

4.2.3. State policies and closing resource loops

Thus far, policies related to labeling, food donation, and animal feed have been assessed as indirectly aligned to circular economy strategies because they are primarily aimed at other social goals, namely public health and safety. State policies related to closing resource loops, on the other hand, were found to have a direct connection to wasted food management. But state-level variability and a lack of unifying federal regulation and guidance have resulted in a patchwork of state policies, an outcome that has been shown in other sectors to create inefficiencies for stakeholder compliance (Mann, 2011; Schumacher and Agbemabiese, 2021).

Two types of policy instruments are identified as enabling loop-closing CE strategies: bans on disposing food waste in landfill or combustion pathways (Table 6) and performance standards specifying a

Table 6
State with wasted food landfill bans

State and Policy Name	Covered Entity and Thresholds	Implementation Exclusions and Waivers
Massachusetts Commercial Food Materials Disposal Ban Enacted & Effective 2014	Commercial generators who dispose >0.5 tons/week and per location (threshold reduced from >1 ton/week)	No exclusions. Temporary waivers if waste contaminated, or facility declines waste and generator can't find alternative in a reasonable time.
Rhode Island Refuse Disposal Law Enacted 2014 Effective 2016	Commercial and institutional generators who produce > 52 tons/year (threshold reduced from >104 tons/year) and within 15 miles of authorized recycling facility or has capacity	No exclusions. Waivers granted if tipping fee for waste disposal is less than authorized recycling facility within 15 miles.
Vermont Universal Recycling Law Enacted 2012 Effective 2014	Residential, commercial, and institutional generators produce any amount (threshold reduced from >104 tons/year)	No generator exclusions or waivers, but covered materials exclude meat and meat products composted onsite.
New York Food Donation and Food Scraps Recycling Law Enacted 2019 Effective 2022	Commercial and institutional generators who produce >2 tons per week at a single location	Excludes large cities (>=1 million), hospitals, nursing homes, adult care facilities. K-12 schools, farms. Temporary waivers if total cost is 10% or more than disposal cost, recycling facility within 25 miles does not have capacity, transporter not available, or other unique circumstances.

Sources: Sandson & Broad Leib (2019), REFED, (2022), 310 MASS. Code Regs. 19.017 (2022), New York State DEC (2022), Rhode Island (2022). Vermont DEC (2020, 2022).

Table 7
States with wasted food diversion requirements

State and Policy Name	Covered Entity and Thresholds	Implementation Exclusions and Waivers
Connecticut Commercial Organics Recycling Law Enacted 2011 Effective 2014	Commercial generators who produce >26 tons/ year by location before donation of source separated organic material (threshold reduced from >52 tons/ year, originally 104) and located within 20 miles of authorized recycling facility with capacity	Excludes K-12 schools, universities, one-time events. Wasted food can be donated or sent to authorized recycling and animal feed facilities.
California Mandatory Commercial Organics Recycling Enacted 2014 Effective 2016	Commercial and institution generators who produce >4 cubic yards/week of organic waste (threshold reduced from >8 cubic yards/ week) and/or 2 or more cubic yards per week of commercial or multifamily solid waste (reduced from 4 or more cubic yards per week)	Excludes Rural counties (populations <70,000), generators that lack sufficient storage space for bins, multifamily buildings, and existing actions or programs already meeting organic recycling goals. No economic, distance, or facility capacity waivers.
New Jersey Food Waste Recycling and Food Waste-to-Energy Production Law Enacted 2020 Effective 2021	Commercial and institutional generators who produce >52 tons/ year by location, and within 25 road miles of authorized facility with capacity	No exclusions. Waivers granted if cost of transporting food waste and recycling fee of facility within 25 miles is at least 10% or greater than total disposal cost. Allow onsite composting or recycling with alternative authorized method.

Sources: NJDEP (2021,2022), CalRecycle (2021a, 2021b), Sandson & Broad Leib (2019), REFED (2022), Connecticut (2022), Connecticut DEEP (2014, 2022)

landfill diversion target (Table 7). The disposal bans prohibit generators from using the landfill pathway for organic waste but do not specify what to do with wasted food instead. The performance standards prescribe specific actions, such as participating in organics collection programs and/or sending food waste to composting or anaerobic digestion facilities. To date, only four states have enacted a food waste disposal ban (New York, Massachusetts, Rhode Island, Vermont) and three states have diversion requirements (California, Connecticut, New Jersey). The majority of state policies are applied to a limited set of commercial and institutional generators. Vermont, however, includes all generators - even households - as of July 2020.

Most states followed a phased-in approach to build up capacity by setting a relatively low threshold for compliance and then increasing coverage over time. For example, Connecticut initially only regulated covered entities that generated more than 104 U.S. tons per year (1 ton per week), a limit that was lowered twice to include any entity generating 26 tons per year as of January 2022 (Connecticut DEEP, 2022). This phased-in approach allows time to build organic waste treatment facilities, expand hauling capacity, and educate and engage targeted stakeholders (Sandson and Broad Leib, 2019). For example, states with a ban or diversion standard have sought to expand treatment capacity by expanding anaerobic digestion facilities on farms to co-process food waste, an approach seen in New York and California (U.S. EPA, 2022). California also reports the highest number of haulers that provide source separation of organics (U.S. EPA, 2022), which is critical to successfully closing the loop. Currently, Vermont is the exception to the threshold approach, in that it prohibits all food scraps from being disposed in landfills, regardless of generator size.

States also vary significantly in elements of policy design that influence practical application. Most state bans and diversion standards rely on mass-based standards; California's diversion requirement is volumetric. Each state specifies different food materials specifically covered by the policy, but all generally define wasted food as human produced or consumed food or material that is made of vegetable, fruit, fish, animal byproducts, grains or others generated during pre- or post-consumer supply chain phases. New York and Rhode Island also include soiled or non-recyclable paper. States also vary in the exemptions available to reduce compliance requirements under specific situations. In the case of Massachusetts, the only state where the threshold is set based on amount of food ultimately disposed, generators can avoid compliance requirements if they reduce total landfilled food waste below the regulatory threshold by donating surplus, processing excess onsite, or sending wastes to composting, animal feeding, or anaerobic digestion (310 MASS. Code Regs. 19.017, 2021). Further, many policies allow waivers if the compliance cost to the food waste generator is significantly higher than what would be required to landfill or otherwise discard the wasted food. Similarly, exemptions may be available if the food waste generators are located more than a specified distance (typically 15–25 miles) away from a waste treatment facility with capacity to accept their waste. California also exempts rural areas, which are estimated to contribute only about 1% to total organic waste in the state (CalRecycle, 2021).

One final point of variability was identified in the potential for these policies to help advance multiple CE pathways. For example, New York's food waste ban also explicitly focuses on donation, with a goal to "increase the donation of wholesome food to those in need" and a requirement that generators "must separate their edible food for donation for human consumption from food scraps designated for recycling or disposal to the maximum extent practicable" (Title 22, Article 27 of New York State Environmental Conservation Law). California has recently extended regulations (SB 1383) to include recovery of 20% of edible food for human use by 2025 (CalRecycle, 2021). These approaches are unique, as most waste management policies tend to ignore prevention measures and focus on recycling or diversion metrics alone (Thyberg and Tonjes, 2016). While many regulations are part of existing solid waste management policies, New Jersey's diversion requirement is the only one that specifically names waste-to-energy as an authorized recycling pathway (N.J. Stat. Ann. § 13:1E-99.122-125, 2021), along with onsite treatment and offsite agricultural use. In general, policies did not specify bioprocesses or conversion pathways for diverted food waste, potentially missing an opportunity to encourage growth of a circular bioeconomy model using wasted food as a feedstock.

The myriad approaches and diversity of provisions within state laws that directly govern food waste diversion and recycling may cause inefficiencies for businesses that operate at a regional or national scale. This confusion may arise from how adjacent states cover institutional and commercial entities and the variety of thresholds and exemptions. A waste hauler or treatment technology provider may face greater market and reporting barriers if seeking to expand operations into nearby states. On the other hand, policy can also play a role in lowering these barriers. For example, market-based incentives or assistance policies that encourage investment in treatment infrastructure can divert additional waste and make these systems more cost competitive (Shahid and Hittinger, 2021). Other barriers to loop closing that are not currently addressed by policy include low landfill tipping fees (U.S. average of $54/ton in 2021 according to EREF), the lack of byproduct markets for composting or biofuels, and regional variability in waste produced (Armington et al., 2020) and market value of bioenergy products (Badgett and Mibrandt, 2021).

While this analysis focused on federal and state policies, municipalities also play a role in closing the loop on food waste. Examples include food and organics waste bans (Seattle, Washington) and landfill diversion targets (Austin, Texas; Boulder, Colorado; Minneapolis and Hennepin County, Minnesota; New York City, New York; Portland, Oregon; and San Francisco, California). Unlike the majority of states, most municipalities extend requirements to residential stakeholders (Sandson and Broad Leib, 2019). Like policies promulgated at higher scales, municipal laws also have significant variability that may make regional solutions challenging to implement. While most focus on waste diversion, Denver, CO has targets that aim to divert 57% of residential food waste and reduce 55% of food-insecure households by 2030 (NRDC, 2019). These policies also vary in compliance thresholds. For example, New York City and Austin policies estimate food waste based on square footage of a generator's facility rather than specifying a mass-based compliance threshold. Facility size and other waste proxies are easier to estimate than food waste mass, but they may not be an accurate indicator (Armington et al., 2020). Future research is needed to analyze municipal policies and understand the extent to which successful models can be generalized to other regions.

5. Implications, recommendations, and broader research needs

Our research finds a limited number of federal policies have the potential to directly enable the circularity of waste food, but lack enforcement mechanisms and are not easily assessed with available data. On the other hand, states have enacted enforceable policies that both directly and indirectly influence the food systems, but many are anticipated to hinder CE goals, either because they may inadvertently lead to increased food wasted or because variability in policy design may confound circular business models. Lessons learned from other waste management systems show that such a "policy patchwork," like the fragmented state policy landscape for U.S. electronic waste management (Kahhat et al., 2008; Ogunseitan et al., 2009; Hickle, 2014), can lead to confusion amongst stakeholders and suboptimal development of collection and recycling infrastructure (Schumacher and Agbemabiese, 2021; Tansel, 2017; Li et al., 2015).

Thus, one tension highlighted by this work is the balance between the standardization possible through uniform federal laws and the flexibility provided by state regulations. Developing uniform centralized food waste policies, as seen in broader CE policies in China and the EU, may reduce compliance costs and create competitive advantage by avoiding the varied state and local regulations. On the other hand, regulating some aspects of wasted food at the state level provides a mechanism for flexibility that can respond to regional variability in waste generation (Armington et al., 2020) or bioresource recovery opportunities (Leipold and Petit-Boix, 2018). Policy analyses in other regions have shown that a mix of policy tools and implementation support mechanisms are required to achieve CE goals and wasted food solutions, due to the underlying variability in food producing industries, socio-economic factors, and markets for byproducts across varied regions within a country (D'Adamo et al., 2021; Righettini and Lizzi, 2020). This variability is certainly observed in the U.S. (Fig. 4), wherein wasted food generation, economic drivers (e.g., landfill tip fees), and CE infrastructure (specifically food banks and anaerobic digestion facilities) vary widely across states. This variability arises from underlying demographics, such as where the largest population is concentrated (California, Texas, Florida, New York), in the spatial distribution of the food supply chain, and in the availability of infrastructure for disposing or managing wasted food (or lack thereof).

Thus, one recommendation is to prioritize federal standardization where it may provide the greatest benefit to preventing wasted food and resolve the greatest points of variability. Specifically, there is a major need to harmonize date labeling requirements and language, so consumers and downstream commercial stakeholders clearly understand what these labels mean (protect public health and safety or promote quality or freshness) (Evans and Nagele, 2018). Achieving such standardization will require significant private and public partnerships; studies on other policy domains show that such collaborations can lead to innovative solutions and reduced business operating and compliance costs when operating across regulatory borders (Gatto and Drago, 2021; Gatto, 2020). Efforts in this regard include policies such as the Food Date Labeling Act, which was reintroduced for consideration in December 2021, and allowing 'wholesome food' to be sold past date (Sevilla, 2021). In our analysis, shellfish, eggs and dairy were the most common food products covered by state date label laws, suggesting that these would be logical targets for federal policy standardization.

Conversely, the wide regional variation in food waste generation,

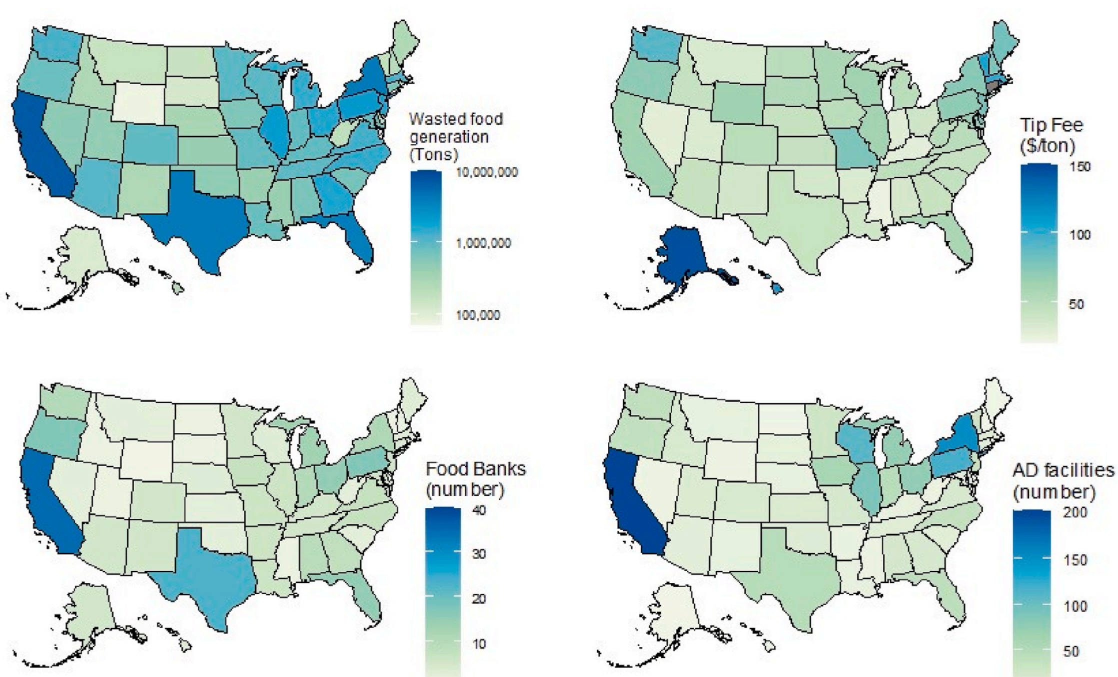

Fig. 4. State variability in drivers of wasted food management. Note that wasted food generation data are specific to industrial, commercial, and institutional sectors only (does not include residential) and are presented on a log scale due to wide differences between states. Wasted food generation, food bank, and anaerobic digestion (AD) facility data are taken from the U.S. EPA Excess Food Opportunities Map (U.S. EPA, 2022a); tip fee data are compiled by the Environmental Research & Education Foundation (EREF, 2021; grey represents no data available).

economic drivers, and infrastructure suggest that policies will also require state-specific action. For example, states can encourage food rescue by adding additional donation liability protection and tax relief beyond what exists at the federal scale. Further, research investments are required to understand whether bans on feeding wasted food to animals serve the purpose of protecting animal and public health and to develop safe, effective, and environmentally friendly heat treatment methods. Centering such policies on the local issues and on the people and businesses within each state and region is expected to provide greater long term economic and social value (Gatto, 2020). Further, state policies can be improved by designing implementation and exceptions that are more consistent at the regional scale. One potential model is the regional approach to climate change mitigation in the U.S. For example, the Regional Greenhouse Gas Initiative is a mandated cap and trade policy that covers 11 states in the northeast region, six of which also have landfill bans or waste diversion policies (C2ES, 2022).

A regional approach may also allow for the consideration of the potential interactions between food waste, climate, and energy policies (Franchetti and Dellinger, 2014). Closed-loop solutions like waste-to-energy systems typically convert food waste into bio-electricity or a biogas, both of which can be sold to displace fossil alternatives and to augment a facility's revenue streams. However, the electricity or fuel prices that can be attained are strongly influenced by climate policy instruments like renewable energy credits and low carbon fuel standards (Smith et al., 2021). Increasing diversion of food waste from landfills to anaerobic digesters can conceivably contribute to meeting both waste and climate targets (Shahid and Hittinger, 2021), but these are rarely considered as a joint goal in policy making.

However, even with a stronger policy environment for wasted food, the challenge remains as to comparing performance of instruments or CE strategies. This research did not address such a question, primarily because data do not yet exist that would allow for analysis of costs and benefits of policy alternatives. To carry out such an evaluation, similar to the EU FUSIONS project, the U.S. will need to first enhance its data and computational infrastructure surrounding wasted food generation and management (Babbitt et al., 2022). Currently, data used by federal agencies typically come from secondary sources (Xue et al., 2017), are collected using a wide range of accounting methods (Spang et al., 2019), are often self-reported by individuals and organizations (Quested et al., 2020) and do not always capture the inherent variability in food waste quantity, composition, or seasonality (Armington et al., 2020). Public data on food waste generation in the U.S. primarily focuses on commercial and institutional generators and does not fully capture agricultural losses and consumer waste.

Such data would also help meet a parallel research need: systemic evaluation of costs and benefits of alternate CE strategies. We anticipate that narrowing resource loops through food waste prevention may provide the greatest benefit in reducing cost and greenhouse gas emissions (Bernstad and Andersson, 2015). Resource loop slowing policies that maintain the nutritional value of the food to feed people have the potential social impact of providing 1.8 billion meals per year and diverting up to 1.1 million tons waste from the landfill, but there are lower economic benefits for animal feeding policies due to high costs of treatment (ReFed, 2016). Policies that encourage donation do not necessarily reduce surplus food (Redlingshöfer et al., 2020), and economic savings may be vulnerable to the rebound effect (Caldeira et al., 2019). On the other hand, the environmental and economic impacts of loop closing strategies such as composting, anaerobic digestion, and other bioeconomy pathways may vary significantly according to local conditions and even analysis methods applied, but are generally found to be preferable to landfilling or incineration (Ebner et al., 2018; Industrial Economics, Incorporated, 2017; Joshi and Visvanathan, 2019; Redlingshöfer et al., 2020; Slorach et al., 2019). Resolving such uncertainty requires parallel advances in systems-level modeling tools, like life cycle assessment, life cycle costing, and social hotspot analysis (Mak et al., 2020; Singh et al., 2021).

Collaboration with partners across the food supply chain is critical in developing structural changes to food policy (Mourad, 2016). This may also include an expansion beyond direct activities in the food system to jointly consider and evaluate technologies like blockchains, sensors, improved packaging, routing logistics, and biodegradable plastics as potential ways to improve efficiencies and reduce risks (Caldeira et al., 2019; Babbitt et al., 2022). In addition, consideration of social factors (Rusciano et al., 2019) is needed to understand how underlying drivers of social responsibility may reduce waste along the supply chain. For example, policies aimed at preventing or reducing wasted food must take into account underlying consumer preferences, values, and beliefs (Babbitt et al., 2021; Benyam et al., 2018; Filimonau et al., 2020; Di Talia et al., 2019) and focus on efforts to 'nudge' behavior modification without requiring attitude changes, increased effort, or education (Hebrok and Boks, 2017). While regulated industries seem to favor flexible market-based approaches, other advocacy groups prefer regulations that guarantee pollutant or waste reductions (Brooks and Keohane, 2020).

6. Conclusions

Current approaches to wasted food management in the U.S. lead to significant economic, environmental, and social impacts. The circular economy framework offers pathways to conserve resources and reduce cost, recover surplus food to benefit public health, and recycle food waste as a bioeconomy feedstock to recovery the energy and resources therein. However, implementation of circular economy strategies is hindered by both the lack of comprehensive federal policy that would catalyze competition and infrastructure development and the presence of a heterogeneous state policy "patchwork" that is expected to create greater confusion for stakeholders and potentially increase costs of compliance. One of the most striking examples of this patchwork is seen in the food date labeling laws that differ across each of the states that have enacted this kind of regulation. Harmonizing the terminology and coverage of date label has significant potential to reduce wasted food across the supply chain.

Mapped against the circular economy framework, there are a handful of U.S. federal policies that directly aim to narrow, slow, and close resource loops, but they largely lack enforcement mechanisms. Further, federal and state policies are typically siloed, failing to capture the interacting nature of circular solutions that don't just address waste, but also provide resource efficiency, cost savings, public health, and new revenue streams. A comprehensive federal circular economy policy could potentially solve this challenge, but this prospect faces immense barriers given the fragmented approach to policy in the U.S. The most concrete and direct enablers of wasted food circularity were observed in the limited number of state policies that either ban landfill of food or require diversion into reuse and recycling pathways. However, these instruments are also varied, particularly when it comes to who is required to comply, what materials are managed, how compliance is achieved, and what exemptions are allowed. This heterogeneity limits the potential for regional solutions, wherein business models, transportation networks, and recovery infrastructure could more easily serve multiple states if the regulatory environment were more consistent. Wasted food policy is still relatively nascent in the U.S., and there is immense opportunity to learn from these challenges to shape future approaches. This trajectory will be enhanced by expanding capacity to collect data describing wasted food generation and management and by developing new systems models that can quantify and communicate systems-level sustainability tradeoffs to inform policy decisions.

CRediT authorship contribution statement

Erinn G. Ryen: Conceptualization, Methodology, Writing – original draft, Data curation, Investigation. **Callie W. Babbitt:** Writing – original draft, Writing – review & editing, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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