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Unintended food safety impacts of agricultural circular economies, with case studies in arsenic and mycotoxins

Christian Kelly Scott[1] & **Felicia Wu**[1,2]

For millennia, food systems worldwide have employed practices befitting a circular economy: recycling of agricultural and food waste or byproducts, environmentally sustainable production methods, and food preservation to reduce waste. Many modern-day agricultural practices may also contribute to a circular economy through the reuse of waste products and/or reducing agricultural inputs. There are, however, food safety impacts. This paper describes two sustainable agricultural practices that have unintended positive and negative impacts on food safety: alternative rice cultivation practices and no-till agriculture. We highlight how alternative rice cultivation practices have intended benefits of water conservation and economic savings, yet also unintended effects on food safety by reducing foodborne arsenic levels while increasing cadmium levels. No-till agriculture reduces soil erosion and repurposes crop residues, but can lead to increased foodborne mycotoxin levels. Trade-offs, future research, and policy recommendations are discussed as we explore the duality of sustainable agricultural practices and food safety.

Agriculture in the circular economy is often referenced in terms of sustainable food systems. While minimizing food waste, food loss, and pollution is often the introductory entry point into the discussion of food, the interconnectedness of the principles of the circular economy also includes repurposing/reusing products and materials and regenerating natural systems[1–3].

Yet another important component of sustainability is health—not only the health of ecosystems but also human health. Agricultural practices focused on advancing the usefulness of byproducts, like crop residuals and soil management, and/or practices that focus on regenerative cultivation techniques to conserve water and limit inputs, like alternate wetting–drying cultivation (AWD) and furrow irrigation (FI), can have important unintended impacts on food safety—with either human health risks or benefits. Figure 1 demonstrates where these issues fit conceptually within the circular economy. In this paper, we present the evidence of unintended food safety impacts stemming from agricultural practices generally regarded as sustainable: alternative cultivation practices for rice (ACP) and no-till agriculture, in the circular economy and the resulting food system.

The current global food system is arguably less oriented around sustainability and more focused on economic viability and food availability. As a result of this emphasis, agricultural production has increasingly moved towards large-scale production, crop monocultures, mechanized farming, and yield maximization. Conventional market production for agricultural products is both highly resource-intensive (land, water, chemical inputs, fossil fuels) and impactful to the environment. A shift in agricultural production away from conventional practices can help to abate these concerns. For many, novel agricultural practices that are integrated into the circular economy paradigm represent the way forward: a focus on sustainability in the food system while improving access to safe, sufficient, healthy, and nutritious food for the world's growing population.

In the circular economy, a change in agricultural policy or practice that is focused on one aspect of the food system sector can have numerous unintended impacts in other areas. For example, previous work focusing on agricultural products resulting from the circular economy includes the promotion of oilcakes that reduce food waste having unintended antinutritional impacts on human food and animal feed[4]. By contrast, plant byproducts in the application of the circular economy in the food system can have positive unintended impacts through human consumption of more nutritional products[5] or environmental benefits of using fewer chemical inputs[6]. Other scholars have noted that targeted changes focusing exclusively on food safety can have widespread unintended impacts throughout the economy and food system[7].

However, in this area of growing scientific inquiry, little attention has been given to how agricultural practices regarded as sustainable may have unintended consequences on food safety. In the examples presented below, we demonstrate how those risks can unintentionally be decreased with ACP of rice or increased with no-till cultivation.

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[1]Department of Food Science and Human Nutrition, Michigan State University, East Lansing, MI, USA. [2]Department of Agricultural, Food, and Resource Economics, Michigan State University, East Lansing, MI, USA. e-mail: fwu@msu.edu

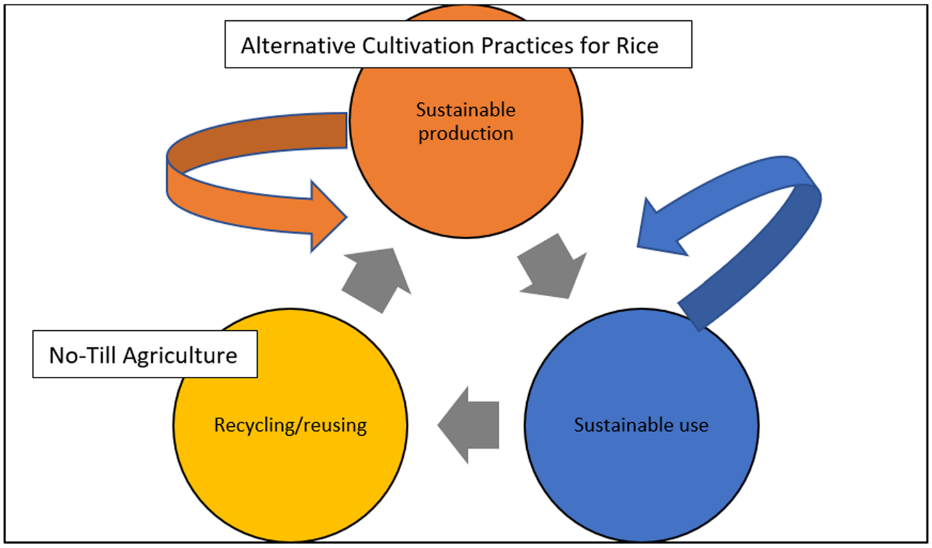

Fig. 1 | Conceptual diagram of two agricultural practices, generally regarded as sustainable, in the circular economy. Figure shows the progression of sustainable production in an orange circle containing a self-loop and a progression to a blue sustainable use circle. Sustainable use circle contains a self-loop and a progression to yellow circle recycling/reusing. Recycling/reusing is linked to sustainable production. No-till agriculture text box is placed within the recycling/reusing circle. Alternative cultivation practices for rice text boxes are placed in the sustainable production circle. The figure demonstrates alternative cultivation practices for rice are a form of sustainable production through reduced water use, no-till agriculture prevents soil erosion and reuses crop residue for soil protection and nutrients, and sustainable use of water and residues relates to both these practices. Authors original creation referencing van Buren et al.[3] and Helgason et al.[2].

Alternative cultivation practices for rice: reduced water use and food safety benefits and risks

For thousands of years, rice has been cultivated around the world in highly water-intensive ways: most often, farmers will keep paddies continuously flooded from early rice plant growth stages through to harvest. Indeed, continuous flooding can be regarded as the conventional rice production method worldwide. Alternative cultivation practices for rice (ACPs), on the other hand, are methods to reduce water use throughout the rice growing season. Two practices that are receiving growing attention in this area are alternate wetting–drying (AWD) and furrow irrigation (FI) cultivation. AWD is the practice of intermittent flooding of fields as opposed to keeping a field flooded throughout the growing stages of the crop. FI is the practice of cultivating rice along elevated beds to deliver water to plant roots from an irrigation system pumping water into furrows without flooding the entire field.

These ACPs have gained traction for three primary reasons relating to the circular economy paradigm: water conservation, reduced greenhouse gas emissions, and reduced input costs. However, the traditional continuous flooding method of rice production had its rationale in maximizing yield and reducing weed damage. Therefore, a reasonable concern is whether ACPs can provide rice yields similar to those afforded by conventional continuous flooding production.

In addition to these economic considerations, an important question is whether using ACPs can reduce the uptake of soilborne arsenic into rice. Arsenic, a naturally occurring metalloid in soil and water, has been known for thousands of years to cause toxicological effects in humans and other animals. Today, humans worldwide are exposed to arsenic through drinking water and food. Under continuously flooded conditions, rice plants take up soilborne arsenic easily through all parts of the plant, including the rice grains. If the soil is not continually wet, arsenic uptake is reduced. Hence, in both AWD and FI cultivation practices, lower arsenic levels may accumulate in rice. This would be an additional benefit of these ACPs. Conversely, however, any soilborne cadmium (also naturally occurring in water and soil) may be taken up more easily when soil is dry: the difference in these cases is that soilborne arsenic is often in the form of anionic metalloids (more easily taken up by plants in wet conditions), while soilborne cadmium is in the form of cationic metal ions (more easily taken up by plants in dry conditions).

No-till agriculture and the risk of foodborne mycotoxins

No-till agriculture refers simply to the practice of forgoing tilling (turning over the soil) on farmlands, either before planting, after harvest, or both. Tilling is common on agricultural fields to remove weeds at the start of the planting season, as well as to remove crop residues after harvest. This practice can, however, increase risks of soil erosion and loss of important soil nutrients for crop plants. No-till agriculture is seen as a potentially more sustainable method of farming; crop residues after harvest are left on the soil to protect nutrients and to prevent erosion.

However, when crop residues are left on farm fields, they can harbor microorganisms and fungal sclerotia, which can then infect the crops planted on those fields in the next season. In the case of overwintering fungi that then colonize crops in the next season, the risk is that some of these fungi produce mycotoxins (fungal toxins) that cause a variety of adverse health effects to humans and animals. The state of the evidence linking no-till practices to mycotoxin risks in subsequent seasons is explored in this paper.

Results

Alternative cultivation practices for rice: impacts on yield, water use, and arsenic levels

The link between alternative cultivation practices (ACPs) for rice production and targeted outcomes (both positive and negative) has been examined in multiple studies, shown in Table 1. These ACPs—specifically, alternate wetting–drying and furrow irrigation—have been tested extensively and shown to reduce water usage and abate water scarcity concerns[8–25]. The practices are useful for the environmental conservation of fresh water and reducing the economic costs of farmers by reducing the use of inputs (like fuel used to power irrigation in AWD)[8,15,26–29]. The practices reduce run-off from fields and aid in rainfall capture efificacy[8,15,25,30,31]. AWD and FI have also been shown to reduce greenhouse gases and emissions compared to continuous flooding[10,32–37]. These benefits are notable, given evidence that suggests that, under the proper conditions, there is no reduction in yield in AWD or FI rice compared to continuous flooding cultivation[8,10–14,17–20,38–45]. These are practical financial and environmental reasons for ACPs to further the principles of the circular economy while preserving rice farmers' overall profitability.

Nonetheless, it is important to consider the food safety impacts of these ACPs. In continuous flooding (conventional) cultivation, the anaerobic conditions lead to increased phyto availability and uptake of soilborne arsenic by rice plants[46–49]. Arsenic is a metalloid that occurs naturally in soils and water worldwide and causes multiple adverse effects in humans: acute toxicity at high doses, several human cancers—most notably lung cancer, skin cancer, and bladder cancer, hyperkeratosis and black foot disease, and cardiovascular disease[50–59]. In multiple studies worldwide, AWD and FI cultivation practices have shown reduced arsenic levels in rice[8,10,15,30,39,43–46,60–70]. These studies are summarized, with corresponding

Table 1 | Studies demonstrating alternative rice cultivation practice outcomes

Outcome	Alternate wetting–drying	Furrow irrigation
Reduced arsenic	Li et al.[39]; Linquist et al.[10]; Price et al.[60]; Rahman et al.[61]; Williams et al.[123]	Aide and Beighley[62]; Duxbury and Panaullah[15]; Li et al.[43]; Stevens et al.[63]; Talukder et al.[64]
Reduced water use	Bouman and Tuong[23]; Lampayan et al.[13]; Linquist et al.[10]; Liu et al.[21]	Bouman et al.[44]; Bouman et al.[14]; Duxbury and Panaullah[15]
Reduced inputs	Kürschner et al.[28]; Massey et al.[8]; Nalley et al.[27]	Duxbury and Panaullah[15]; Hogan et al.[26]; Vories et al.[29]
Reduced carbon emissions	Li et al.[37]; Lindau et al.[34]; Linquist et al.[10]; Wassmann et al.[36]	Feng et al.[33]
Rainfall capture / reduced runoff	Li[25]; Martini et al.[30]; Massey et al.[8]	Duxbury and Panaullah[15]; Majumdar et al.[31]
Comparable yield to conventional methods	Das et al.[65]; LaHue et al.[11]; Lampayan et al.[13]; Li et al.[41]; Li et al.[39]; Rahman et al.[61]	Bouman et al.[14]; Duxbury and Panaullah[15]; Li et al.[43]; Stevens et al.[75]
Reduces yields	Bouman and Tuong[23]; Carrijo et al.[12]; Hu et al.[66]; Yamaguchi et al.[77]	Bouman et al.[44]
Increased labor demands	Carrijo et al.[12]; Linquist et al.[10]; Massey et al.[8]; Miller et al.[76]	Stevens et al.[75]
Reduced soil carbon content	Pan et al.[80]; Wu[81]	Witt et al.[82]
Increased cadmium	Arao et al[83]; Honma et al.[84]; Hu et al.[66]; Li et al.[39]; Yang et al.[38]	Zhao and Wang[87]

arsenic reductions in ACPs vs. continuously flooded rice, in Table 2. In practice, therefore, these ACPs could reduce human exposures to foodborne arsenic, with potentially significant health effects—especially for populations where rice is a dietary staple. Indeed, policymakers worldwide are increasingly focusing on reducing arsenic in food. In the United States, the Food and Drug Administration (FDA) is implementing a Closer-to-Zero Action Plan, with the intent of setting action levels for foodborne arsenic, cadmium, lead, and mercury by 2024. This was followed by a US Congressional Report in 2021, describing high levels of arsenic, cadmium, lead, and mercury in infant foods pulled from grocery shelves[71–74]. As rice is a common component not just in adult diets but in infant foods, it is all the more critical to find methods to reduce arsenic levels in rice.

ACPs, however, are not uniformly beneficial to human welfare and the environment. ACPs can be tactically demanding compared to continuously flooding rice[8,10,12,75,76]. If a field has soils that dry out quickly, yields can be reduced substantially, even if the other benefits of the practice, such as arsenic reduction, are increased[10,12,23]. In general, ACPs are often associated with reduced yields compared to continuous flooding cultivation[12,44,66,77,78]. Many studies have examined the relationship between rice yields under conventional vs. alternative cultivation practices, summarized in Table 3. Adoption of ACPs has been slow because they are often difficult to scale up, and, in the case of quickly drying soils, present potential economic risks to farmers who cannot afford to switch rice cultivation techniques for a relatively unproven practice[8,10,12,13,27,28,79]. Some studies suggest that ACPs may be related to decreased carbon availability in soils[80–82].

There is a countervailing potential food safety risk as well, in that drier soils have increased bioavailability of cadmium that can be taken up by the plants, thereby increasing the consumption of the harmful metals and metalloids in diets[39,66,68,83–85]. Several studies have demonstrated the link between ACPs and increased cadmium uptake in rice, as shown in Table 4. Cadmium exposure has been associated with diverse cancers and with neurotoxic and nephrotoxic effects[86]. This is far from an ideal solution, with increased exposure to cadmium as arsenic decreases in alternate wetting-drying rice production. Even so, from a public food safety risk perspective, arsenic is generally regarded as the more toxic element compared to cadmium, from a human health perspective[87]. Moreover, interestingly, cadmium uptake in rice has been shown to be correlated with other essential elements such as copper and selenium[88], which may help to reduce the biologically effective dose of cadmium in the body. Hence, in a literal 'pick your poison' decision, reducing arsenic levels through ACP has been considered preferable to reducing cadmium levels in continuous flooding cultivation[39,68,87]. Nevertheless, ACPs are not all-or-nothing strategies, and farmers must often weigh the specific amount of flooding and dry field management in a manner that provides an optimal reduction in both arsenic and cadmium uptake by their crops[39,68,87–89].

No-till crop cultivation: impacts on mycotoxin concentrations in crops

Mycotoxins are toxic and carcinogenic chemicals produced by fungi that colonize crops[90]. Among the most agriculturally important mycotoxins worldwide are aflatoxins, produced primarily by *Aspergillus flavus* and *A. parasiticus*; fumonisins, produced primarily by *Fusarium verticillioides* and *F. proliferatum*; deoxynivalenol (DON, vomitoxin) and zearalenone, produced primarily by *F. graminearum* and *F. culmorum*; and ochratoxin A, produced by *Penicillium verrucosum* and *A. ochraceus*[91]. These mycotoxins, which can co-occur in field conditions[92], cause a diversity of harmful health effects in humans and animals, ranging from liver cancer to neural tube defects in babies to immunosuppression and growth impairment. These fungi frequently colonize crops such as maize, nuts, and cereal grains in the field, where they may produce these mycotoxins; and can also continue to grow in storage or to overwinter in fields, particularly if crop residues are still present.

One growing practice that is often discussed in the context of the circular agricultural economy is no-till agriculture—in which crop residues play a key role. No-till agriculture is a practice of soil management that involves minimal disruption of the topsoil both before planting and after harvest. Where much of the conventional contemporary farming practices involve turning over the topsoil and crop residues following the harvest to prepare the soil for the next season's crops, no-till farming involves minimal soil disturbance between harvest and planting and typically means leaving crop residue on fields. The practice of no-till agriculture has several important economic, environmental, and health benefits: it can preserve soil organic carbon, improve biodiversity, reduce soil erosion, reduce labor and agricultural input costs, and reduce emissions of $PM_{2.5}$[93–97].

However, the discourse around no-till farming has almost exclusively focused on comparison to conventional tilling of agricultural and environmental outcomes, such as yields, soil health, weed abundance, and ecosystem services; with little attention given to the quality and safety of the food crops produced in each scenario[98–101]. Indeed, non-tilled soils may retain harmful characteristics that conventional tilling could reduce or eliminate. It has been shown that pathogens may survive more efficiently and colonize the following season's crops under no-till conditions[102–105]. Untilled soil may result in immobilized nutrients, leading to problems with crop nutrition availability and uptake[105–107]. In many commercial fields, no-till cultivation has led to greater use of chemical controls for pests and weeds because these are not cleared from the field as they would be if tilled; which may increase human health and ecosystem risks from pesticide and herbicide exposures[101,108]. Specific to food and feed safety, the primary concern of no-till agriculture's effect on the crops grown in following seasons is what some authors have described as 'the mycotoxin problem'[109–111].

Table 2 | Studies linking alternative cultivation practices (ACPs) and water management practices, including aerobic cultivation, alternate wetting–drying (AWD), and continuous flooding (CF), to arsenic content in rice grains

Citation	As in grain (in percent change ACP compared to conventional/continuous flooding)	Nation(s)	ACP result
Linquist et al.[10]	AWD = ↓64% or limited reduction	AR, USA	Limited or reduced
Xu et al.[45]	↓62–66%	United Kingdom	Reduced
Hu et al.[66]	Greenhouse pot: ↓67–94% Int.-Aerobic = ↓56% Intermittent = ↓38% CF = (highest) 0.34 mg kg^{-1} Field: ↓16% Aerobic = ↓33% Int.-Aerobic = ↓33% Intermittent = ↓29% CF = (highest) 0.21 mg kg^{-1}	China	Reduced
Das et al.[65]	Non-flood = ↓53% AWD = ↓50%	Taiwan	Reduced
Rahman et al.[61]	CF = (highest) 0.65 mg kg^{-1} AWD = ↓37%	Bangladesh	Reduced
Hu et al.[68]	↓ 17–52% Aerobic = ↓39% Intermittent Flooding = ↓33% Conventional = ↓19% Flooding = (highest) 0.36 mg kg^{-1}	China	Reduced
Hu et al.[85]	Aerobic = ↓50% Intermittent Flooding = ↓53% Conventional = ↓28% Flooding = (highest) 0.4 mg kg^{-1}		
Arao et al.[83] (inorganic As)	CF = ↓9% Extended flooding = ↓18% Moderate flooding = ↓57% Medium AWD = ↓23% Shorter flooding = ↓75% Mild AWD = (highest) 0.44 mg kg^{-1} Minimal flooding = ↓75%	Japan	Reduced
Hua et al.[69]	CF = (highest) 18.3 μg kg^{-1} AWD = ↓73%	AR, USA	Reduced
Price et al.[60]	Reduces (multiple measures)	Multiple (Bangladesh)	Reduced
Somenahally et al.[67]	AWD = ↓41%	AR, USA	Reduced
Li et al.[39]	AWD = ↓14-61%	CA, USA	Reduced
Takahashi et al.[46]	↓53%	Japan	Reduced
Talukder et al.[64]	AWD = ↓41–45%	Bangladesh	Reduced
Li et al.[43]	Aerobic = ↓87% Flood—Aerobic = ↓25% Aerobic—Flood = ↓46%	United Kingdom	Reduced
Spanu, et al.[124]	CF = 163 μg kg^{-1} Irrigation = ↓98%	Italy	Reduced
Honma, e tal.[84]	CF = ↓6% Mild AWD = (highest) 0.52 mg kg^{-1} Moderate AWD = ↓25% Severe AWD = ↓62% Rain-fed = ↓67%	Japan	More intense reduced

Table 3 | Studies linking alternative cultivation practices (ACPs) and water management practices, including aerobic cultivation, alternate wetting–drying (AWD), and continuous flooding (CF), to rice yields

Citation	Yield (in percent change ACP compared to conventional/ continuous flooding)	Nation(s)	ACP result
Linquist et al.[10]	CF = 10.26 Mg ha AWD/40-Flood = ↓1% AWD60 = ↓5%	AR, USA	Lower
Li et al.[39]; Carrijo et al.[40]	No change	CA, USA	No change
Xu et al.[45]	No change	United Kingdom	No change
Hu et al.[66]	CF = 6.26 tons/ha AWD mix = ↓20% AWD-low = ↓31%	China	Lower
Yang et al.[38]	CF = Control AWD–med = ↑10–12% AWD-severe = ↓33–36%	Yangzhou, China	Mixed
LaHue et al.[11]	No change	CA, USA	No change
Carrijo et al.[12]	Overall = ↓5% Mild AWD = no change Severe AWD = ↓23%	Japan, Senegal, Iran, Uganda, India, China, Philippines, Vietnam, Australia, Nepal, Bangladesh, Brazil, USA, Malawi, Thailand, Indonesia	Mixed
Bouman et al.[14]	CF = 5.8 tons ha^{-1} AWD = ↓26%	SE Asia: China & Philippines	Mixed
Lampayan et al.[13]	No change	Philippines, Vietnam, Bangladesh, India, Indonesia, China, Laos, Myanmar	No change
Bouman et al.[44]	AWD in dry = ↓32% AWD in wet = ↓22%	Philippines	Lower
Massey et al.[8]	AWD = ↑9% CF = 11,396 kg ha^{-1}	MS, USA	Higher
Belder et al.[18]	No change	China & the Philippines	No change
De Vries et al.[19]	Wet season = AWD higher Dry season = CF higher	Senegal	Mixed
Yao et al.[20]	No significant difference	Hubei, China	No change
Das et al.[65]	No yield reduction	Taiwan	No change
Rahman et al.[61]	Not a significant reduction	Bangladesh	No change
Hu et al.[68]	Aerobic = ↓16% Intermittent flooding = ↑1% Conventional = 11.0 tons ha^{-1} Flooding = ↓16%	China	Lower
Hu et al.[85]	↓ 10–20%		
Arao et al.[83]	No yield reduction	Japan	No change

Under no-till agricultural cultivation, crop residues left in the field serve as a refuge for fungal sclerotia to overwinter in the field: to survive between harvest and the next planting. These sclerotia can serve as an inoculum for fungal infection on crops grown in the following season[110–114]. This can pose a food safety danger in that certain fungi produce mycotoxins that contribute to cancer, immunosuppression, and growth impairment in humans; as well as economic losses to farmers[115–118]. The explicit link between the targeted fungal species/fungal mycotoxins and no-till agriculture has been examined in a wide variety of contexts—mycotoxins, fungi, crops, and different geographic regions worldwide—shown in Table 5. While several studies did not find any significant differences in fungal infection rates and mycotoxin levels in no-till vs. conventionally tilled fields, the preponderance of evidence to date is that no-till agriculture results in higher levels of fungal infection and subsequent mycotoxin contamination in crops grown in no-till agricultural conditions.

Given the food safety (and other previously mentioned) concerns, a careful balance between ecological, health, and economic factors must be calculated by farmers in choosing a tillage system for their crops. This is simultaneously a public health, agricultural science, and livelihood-economic calculation. If the agricultural products that farmers produce exceed the limits of consumable mycotoxins, they cannot be sold for human or animal consumption, due to regulations on allowable mycotoxin levels in over 100 nations worldwide. Further complicating the matter is that mycotoxins are expected to become a greater risk in the future due to near-term climate change impacts[118–121].

Discussion

When the agricultural circular economy is discussed in the context of sustainable food production, it is important to consider food safety and food quality impacts. In 2016, Stahel[122] wrote of the circular economy paradigm: "It would change economic logic because it replaces production with sufficiency: reuse what you can recycle what cannot be reused, repair what is broken, remanufacture what cannot be repaired." Later, he states that this paradigm applies to "arable land;" grouped with his discussions of cars, buildings, mobile phones, and cultural heritage. Indeed, since this writing, agricultural studies have examined applications of the circular economy to promote sustainable food production practices. However, somewhat differently from other applications of the circular economy listed in Stahel's article, food safety and its attendant human health effects must be key considerations when it comes to agricultural contexts.

In this review, we described two very different and arguably sustainable agricultural practices befitting of the "circular economy" designation: alternative cultivation practices (ACPs) for rice production that use significantly less water than the conventional continuous flooding method and

Table 4 | Studies linking alternative cultivation practices (ACPs) and water management practices, including aerobic cultivation, alternate wetting–drying (AWD), and continuous flooding (CF: Conventional method), to cadmium content in rice grains

Citation	Cd in grain (in percent change ACP compared to conventional/continuous flooding)	Nation(s)	ACP result	
Hu et al.[66]	*Greenhouse pot*: Int.-aerobic = ↓61% Intermittent = ↓93% CF = 3.25 mg/kg	*Field*: Aerobic = ↑950% Int.-Aerobic = ↑600% Intermittent = ↑50% CF = 0.02 mg/kg	China	Increased (in field)
Hu et al.[68]	Aerobic = ↑1,083% Intermittent Flooding = ↑667% Conventional = 0.06 mg/kg Flooding = ↓50%		China	Increased
Hu et al.[85]	Aerobic = ↑833% Intermittent Flooding = ↑633% Conventional = 0.15 mg kg^{-1} Flooding = ↓87%			
Arao et al.[83]	CF = 0.008 mg kg^{-1} Extended flooding = ↑288% Moderate flooding = ↑3838% Medium AWD = ↑2213% Shorter flooding = ↑4588% Mild AWD = ↑713% Minimal flooding = ↑4025%		Japan	Increased
Li et al.[39]	CF = 6.5 µg kg^{-1} AWD35 = ↑155% AWD25 = ↑322%		CA, USA	Increased
Yang et al.[38]	*Grain*: CF = 0.77 µg g^{-1} Moderate AWD = ↓19% Severe AWD = ↑10%	Milled rice: CF = 0.60 µg g^{-1} Moderate AWD = ↓40% Severe AWD = ↓15%	Yangzhou, China	*Moderate AWD reduced grain and milled rice Cd *Severe AWD increased grain but reduced milled rice Cd
Honma et al.[84]	CF = 0.01 mg kg^{-1} Mild AWD = no change Moderate AWD = ↑100% Severe AWD = ↑60% Rain-fed = ↑1500%		Japan	Increased

Table 5 | Studies linking mycotoxin concentrations in crops to no-till agricultural practices

Mycotoxin	Crop	Significant increase of mycotoxin in no-till fields	No significant increase in no-till fields
Aflatoxin	Maize	Zablotowicz et al.[125]; Abbas et al.[110]; Accinelli[126]; Abbas et al.[114]	
	Multiple	Mejía-Teniente et al.[127]	
Aspergillus flavus	Maize	Abbas et al.[128]; Nesci et al.[129]; Zablotowicz et al.[125]; Abbas et al.[110]; Accinelli[126]; Abbas et al.[114]	McGee et al.[130]; Torres et al.[131]
	Multiple	Horn and Dorner[132]	Angle et al.[133]
	Peanuts	Griffin et al.[134]	
A. parasiticus	Maize	Nesci et al.[129]	
	Multiple		Angle et al.[133]
Fumonisin	Maize	Torres et al.[131]; Abbas et al.[110]	Chulze et al.[135]; Marocco et al.[136]; Arino et al.[137]
	Multiple	Burgess and Bryden[111]	
	Wheat/Barley	Obst et al.[138]	
Fusarium verticillioides	Maize	Nesci et al.[129]	Flett and Wehner[139]; Flett et al.[140]; Mabuza et al.[141]
	Multiple	Burgess and Bryden[111]	
F. proliferatum	Maize	Ramirez et al.[142]; Torres et al.[131]; Nesci et al.[129]	Chulze et al.[135]
	Multiple	Burgess and Bryden[111]	
Deoxynivaleonol (DON, vomitoxin)	Wheat/Barley	Obst et al.[138]; Dill-Macky and Jones[113]; Schaafsma et al.[143]; Labreuche et al.[144]	Spolti et al.[145]
	Multiple	Edwards[146]; Mejía-Teniente et al.[127]; Burgess and Bryden[111]	
	Maize	Mabuza et al.[141]	Abbas et al.[110]; Mabuza et al.[141]
Fusarium graminearum	Wheat/Barley	Burgess et al.[147]; Smiley and Patterson[148]; Obst et al.[138]; Miller et al.[149]; Dill-Macky and Jones[113]; Del Ponte et al.[150]	Pereyra and Dill-Macky[151]; Lori et al.[152]; Spolti et al.[145]
	Maize	Mabuza et al.[141]	
	Multiple	Burgess and Bryden[111]	
F. culmorum	Wheat/Barley	Smiley and Patterson[148]	
Zearalonone	Maize	Abbas et al.[110]	
	Multiple	Burgess and Bryden[111]	
F.graminearum	Maize	Abbas et al.[110]	
	Multiple	Burgess and Bryden[111]	
F. culmorum	Maize	Abbas et al.[110]	
	Multiple	Burgess and Bryden[111]	

no-till farming. In both cases, these practices reduce certain important agricultural inputs such as water and labor, and foster other environmental benefits such as reduced carbon emissions and reduced soil erosion and $PM_{2.5}$ emissions. However, the food safety effects of these practices must be considered in a truly circular paradigm.

In the case of alternate wetting–drying and furrow irrigation production methods of rice production, a key food safety benefit is the reduced uptake of soilborne arsenic into rice grains. This could translate into significantly lower foodborne arsenic exposures, which could lead to meaningful health benefits in populations worldwide where rice is a dietary staple. On the other hand, there is some evidence of increased cadmium uptake in rice grains when ACPs are employed—a tradeoff resulting from the anionic vs. cationic natures of arsenic vs. cadmium in wet or dry soil. The extent to which these concentrations may differ in rice grains under different cultivation practices and the imputed human health effects are important areas to study in the future; as around the world, rice farmers may adopt these ACPs at higher rates due to meeting new food safety standards. Other means of reducing arsenic and cadmium exposure through rice include removal of the hull and bran, which typically bioaccumulate more of these metals; and soaking rice grains and discarding the water before cooking.

In the case of no-till agriculture, diverse microorganisms, including mycotoxigenic fungi, are more likely to survive in fields that contain crop residues—which are common in untilled fields. The overwintering fungi can then colonize the crops planted in the subsequent season, and produce mycotoxins on those crops that pose health risks to humans and animals. There is a large body of evidence for the five most agriculturally important mycotoxins—aflatoxins, fumonisins, deoxynivelanol, zearalenone, and ochratoxin A—that no-till agriculture increases the risk that the fungi that produce these toxins will colonize food crops. Because the aforementioned mycotoxins cause such a wide diversity of serious health effects, this food safety issue must be taken into account when considering the benefits and costs of adopting no-till farming systems. While tilling is far from the only solution to reduce mycotoxin risks—others include good agricultural practices in the field, improved (cool, dry, pest-free) food storage practices, and a variety of plant breeding and chemical application strategies—tillage choices by farmers can have an important impact on this key food safety risk.

Incorporating food safety considerations into sustainable agricultural practices is crucial and, in fact, fulfills the true "circular economy" paradigm by extending to human health effects. Healthier populations are better able to sustainably produce safe and nutritious food worldwide, and the circular nature of human health and agricultural production can result in improved food security while protecting environmental resources.

Methods

We conducted a systematic review of the published literature on alternative vs. conventional rice production practices, with a focus on alternate wetting–drying and furrow irrigation compared with continuous flooding

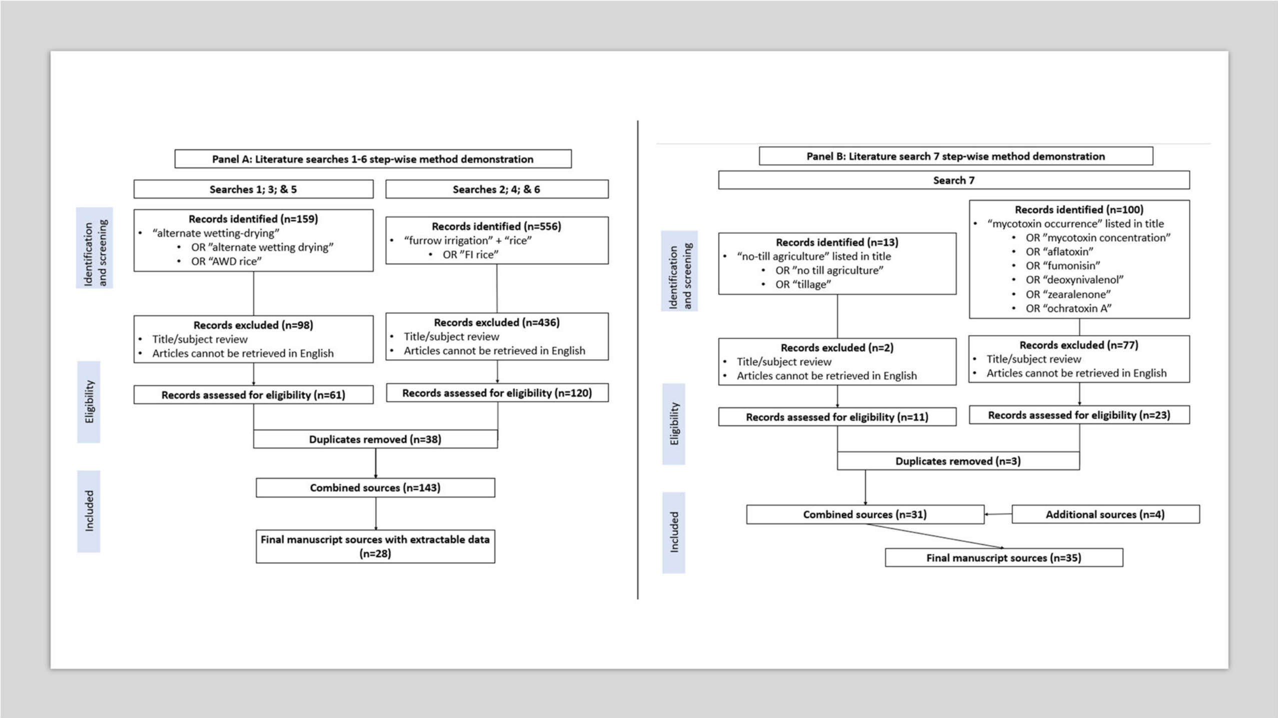

Fig. 2 | Literature search methodology. Panel **A** shows the selection and inclusion criteria of studies related to rice production methods. Search numbers refer to (1) alternate wetting-drying cultivation of rice (AWD) and reduced arsenic; (2) furrow irrigation (FI) and reduced arsenic; (3) AWD and yield; (4) FI and yield; (5) AWD and increased cadmium; and (6) FI and increased cadmium. 1, 3, and 5 on the left with 159 initial records. The primary search term was "alternate wetting-drying" with secondary terms OR "alternative wetting drying" or "AWD rice". The number of studies evaluated at each step is included in the boxes. Panel **B** shows the selection and inclusion criteria of studies related to no-till agriculture and mycotoxin occurrence (Search 7). The primary search term was "no-till agriculture" with secondary "no-till agriculture" or "tillage". Progresses to 2 records excluded due to language/subject review; leading to 11 records assessed. Right side demonstrates 100 initial records identified with "mycotoxin occurrence" in the title. Secondary terms were "mycotoxin concentration", "aflatoxin", "fumonisin", "deoxynivalenol", "zearalenone", or "ochratoxin A". The number of studies evaluated at each step is included in the boxes.

(the traditional and conventional method of rice production). We examined the evidence for a variety of economic and environmental outcomes, as well as the evidence for arsenic and cadmium uptake in each of these cultivation practices. We also conducted a systematic review of the literature on the impact of tilling vs. no-till agriculture on the concentrations of five agriculturally important mycotoxins—aflatoxins, fumonisins, deoxynivalenol, zearalenone, and ochratoxin A—in a diversity of crops. We compared results across studies for concentrations of these mycotoxins in tilled vs. no-till fields.

Boolean search terms were used to conduct a systematic literature review to identify extractable data sources for summary tables for ACP rice/grain impacts and no-till agriculture/mycotoxin relationships. The review consisted of a systematic and additional examination of relevant sources and citations from these documents for additional references (see refs. 1–5). Searching took place in Google Scholar and the Michigan State University Library database search tool. The Michigan State University (MSU) Library database search tool allowed for simultaneous searching from multiple databases. The top identified databases where articles were sourced were Complementary Index; Environmental Complete; Academic Search Complete; and Springer Nature Journals. In total, 7 searches took place (reference in Fig. 2a and b): (1) alternate wetting–drying cultivation of rice (AWD) and reduced arsenic; (2) furrow irrigation (FI) and reduced arsenic; (3) AWD and yield; (4) FI and yield; (5) AWD and increased cadmium; (6) FI and increased cadmium; and (7) no-till agriculture and mycotoxin occurrence. Peer-reviewed publications from the last 30 years (since 1994) were considered for review for the alternative cultivation practices' (ACP) impacts. Detailed review of 143 sources allowed for the identification of 28 sources with extractable data. A study is needed to provide synthesizable evidence of ACP compared to conventional cultivation for the desired impact, arsenic/cadmium content, or yield to be included in our review. For the no-till and mycotoxin review, selection criteria were not limited to the last 30 years and the search criteria stipulated peer-reviewed sources.

The systematic inclusion/exclusion process of studies related to rice cultivation practices and diverse effects, and no-till agriculture and mycotoxin risks, can be seen in Fig. 2a and b, respectively. Our review consisted of extensive consideration of in-text citations and referenced studies drawing from the initial systematic search. However, despite extensive searching, evaluating, and reference-checking, there is a potential for introduced bias in utilizing peer-reviewed publications that are indexed in the MSU database registry and in Google Scholar. By only including indexed, peer-reviewed, and English-language publications, potential alternative perspectives and non-traditional theoretical/methodological approaches may have been excluded from our analysis and presentation of findings.

Data availability

All data generated or analyzed during this study are included in this published article and its references.

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Author contributions

F.W. conceived and developed research questions. C.K.S. preformed analysis and literature review. C.K.S. and F.W. drafted and edited the paper. C.K.S. prepared figures and tables. F.W. provided expertise feedback and project administration/supervision.

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to Felicia Wu.