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Consumers' Acceptance of Agricultural Fertilizers Derived from Diverted and Recycled Human Urine

Alex Segrè Cohen,* Nancy G. Love, Kimmerly K. Nace, and Joseph Árvai

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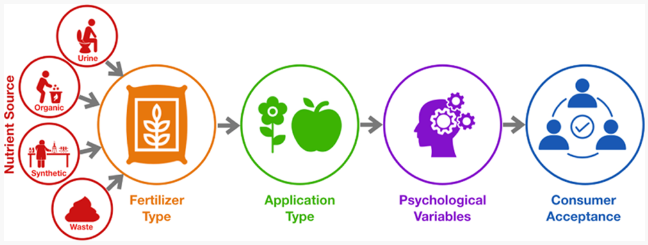

ABSTRACT: Nitrogen and phosphorus are essential ingredients in fertilizers used to produce food. Novel methods are emerging for more efficiently sourcing these nutrients, one of which is to recover them from recycled human urine; once recovered, N and P can be redirected to fertilizer production. While the technology for creating human urine-derived fertilizer (HUDF) exists, implementing it at scale will depend on public acceptance. Thus, this study examined U.S. consumers' acceptance of HUDF across a range of applications and, in comparison, to other fertilizer types. Data were collected from a representative national sample, and analyses of variance with *post-hoc* comparisons were conducted to compare across fertilizer applications and types. A hierarchical regression was conducted to assess if demographics, psychological variables, and value orientations predict HUDF acceptance. Results suggest that HUDF and biosolid-based fertilizers are equally preferred and more strongly preferred than synthetic fertilizers. HUDF is not preferred as strongly as organic fertilizers. HUDF was deemed most acceptable when used on nonedible plants and least acceptable when used on crops for human consumption. Regression analysis revealed that judgments about risks and benefits were the strongest predictors of acceptance of UDF use. These results are promising for sanitation practitioners and regulators among others.

1. INTRODUCTION

The cycling of nitrogen and phosphorus is vital to supporting life on earth.[1,2] Both nutrients are particularly important in agriculture because they are essential ingredients in fertilizers[3] and are, therefore, crucial for feeding a growing world population.[4] While abundant and affordable supplies of these nutrients was once commonplace, constraints on nitrogen and phosphorus have emerged. Conventional nitrogen fertilizer production is energy-intensive, has a large water and carbon footprint, emits ozone-depleting nitrous oxide, and—by way of runoff and wastewater from agriculture—leads to the eutrophication of both terrestrial and aquatic systems and to global acidification.[1,5] At the same time, accessible, affordable, and high-quality phosphate rock reserves are declining.[6] Thus, phosphate prices are vulnerable to global economic fluctuations as evidenced by the twofold increase in super phosphate farm prices between 2005 and 2009. Phosphorus prices are expected to become increasingly volatile in the future, having greater impacts on future global food prices.[7]

Complicating matters further, the present use of nitrogen and phosphorus is inefficient. For example, throughout 15 European countries, only 10% of applied phosphorus reaches consumers.[8] The same is true of nitrogen; unrecovered nitrogen was estimated to be approximately 65% with significant nutrient loss through both wastewater effluent and biosolid disposal.[9] A related study found that only 29% of applied phosphorus made its way to productive use, while 64% of nitrogen was unrecovered.[10]

Considering these challenges, the recovery and recycling of nitrogen and phosphorus from wastewater is drawing the attention of the scientific community, NGOs, and policymakers. While there are several ways to recover and recycle these nutrients (e.g., such as using domestic biosolids or sewage sludge as fertilizer, or recycling ammonia from livestock wastewater), human urine diversion and recycling is emerging as an energy-efficient method of producing high-quality fertilizer for use in agriculture because the vast majority of nitrogen consumed by people is excreted as urine.[11,12] In addition, human urine diversion and recycling recovers phosphorus, nitrogen, and potassium together, producing a more beneficial fertilizer product that is equivalent to mineral fertilizers.[13] Recovering nutrients from human urine and redirecting them for agricultural fertilizers would also increase the energy efficiency and sustainability of food production.[13−16]

Human urine can be processed into different forms of urine-derived fertilizers (HUDF) that are compatible with soil types and agronomy practices across large sectors of the world, including about half of North America.[17] Also, producing

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HUDF has the added benefit of protecting water resources because nutrients and micropollutants (e.g., pharmaceuticals and personal care products) can be removed more efficiently from urine than after it is diluted into wastewater.[12] Technologies such as struvite precipitation, nitrification–distillation, and alkaline urine dehydration are all in advanced stages of development, and some are being used on small-scales for diverting, recycling, and converting human urine for HUDF production.[18−21]

The deployment of infrastructure for urine diversion and HUDF production at scale requires retrofitting or replacing public and building-scale wastewater systems. This task, though formidable, is not impossible. However, building the momentum to turn proof-of-concept into widespread distribution depends on public acceptance.

1.1. Psychological Variables, Consumer Acceptance, and HUDF.

Research on public perceptions of human urine diversion, recycling, and HUDF is beginning to emerge. However, results from these studies are either highly localized or nongeneralizable. For example, in a study of 2700 users of urine separating toilets, Lienert and Larsen[22] observed high levels of support for HUDF; however, these results are expected from a self-selected sample of people who already adopted them in their homes or workplaces. Looking at fertilization methods and nutrient management broadly, researchers observed low levels of awareness and knowledge among consumers.[23] Yet, prior research on consumers' acceptance of fertilization methods shows that organic fertilizers (such as bone meal and compost) are viewed quite positively,[24] and synthetic fertilizers (such as ammonium nitrate and potassium sulfate), in contrast, are not.[25]

The disconnect between low levels of awareness and also strong opinions about fertilizers demonstrate that consumer acceptance is not necessarily only related to objective knowledge about emerging (or established) technologies. Several psychological variables may predict consumers' acceptance of emerging technologies related to the production of food (which we expect to also be the case with HUDF). They include value orientations,[26] instinctive emotional responses such as disgust,[27] generalized perceptions of risk and benefit,[28] and perceived naturalness.[29] However, to date, these variables have received little attention in research on consumers' perceptions of HUDF.

1.1.1. Value Orientations.

People's values serve as guidance for preferences and are used to predict attitudes and behavioral intentions.[26] One approach to account for values is via value-belief-norm theory, which posits that different value orientations (e.g., altruism, biospherism, and egoism) lead to varying levels of acceptance of pro-environmental behavior and technologies.[30] Generally, those with a stronger egoistic value orientation, or a deep regard for one's self-interests and personal well-being, tend to be less amenable to pro-environmental options. On the other hand, those with altruistic (emblematic of high levels of concern for the welfare of others) and biospheric (emblematic of high levels of concern for the environment because of its intrinsic value) concerns tend to prefer pro-environmental outcomes such as technologies with clear environmental benefits.[31]

Value orientations have been used to predict levels of acceptance of controversial or emerging environmental technologies such as solar radiation management,[32] nuclear power,[33] nanotechnology,[34] and genetically modified organisms (GMOs).[35] Urine separation and reuse leading to HUDF production share similarities with solar radiation management and nuclear power in that they all require infrastructure development or retrofits. However, given that the scale of change is smaller than the other aforementioned technologies and because HUDF adoption would call for changes in personal consumption, consumers' acceptance of HUDF is likely to be judged on a more personal (*vs* societal) and environmental level such as GMOs and nanotechnology. Thus, we might expect egoistic and biospheric value orientations to be especially relevant. Regarding the latter, for example, people who ascribe strongly to a biospheric value orientation tend to be more supportive of products and technologies that are in greater harmony with nature; for example, manufacturing processes that rely on recycling ingredients and raw materials that would otherwise be discarded as waste.[26]

1.1.2. Affect and Disgust.

Two parallel systems operate in the mind when people form judgments and preferences.[36] System 1 is intuitive, automatic, and experiential. System 2, in contrast, is analytic, deliberative, and reliant on rational calculation. The defining characteristic of system 1 is termed affect; the rapid and intuitive emotional state that people experience in response to a stimulus.[37,38] Affect consists of positive or negative feelings of arousal (e.g., happiness or sadness) and intuitive assignments of positive or negative valence (e.g., beauty or ugliness) to stimuli. A reliance on system 1 to guide judgment and decision-making was termed the affect heuristic.[37]

Recent research in the food domain extended the influence of the affect heuristic to another important intuitive response: disgust. Disgust is associated with negative valence and arousal; however, studies on food disgust also emphasize its essential, evolutionary roots. Specifically, intuitive feelings of disgust are thought to function as protective mechanisms to prevent animals from ingesting potentially harmful materials.[39]

Research on consumers' acceptance of certain foods supports the connection between affect and disgust. In research on cultured meat and insect protein, for example, high levels of disgust were linked to negative arousal and valence, and to low levels of acceptance.[40,41] While research has not focused on the connection between disgust and HUDF, research on treated wastewater (for human consumption through potable reuse) shows that those who find it disgusting are three times less likely to consume it.[42] Similarly, research on public perceptions of nutrient recycling in treated sewage sludge indicates that disgust is a key factor influencing U.S. consumers' lack of receptivity to biosolid-based fertilizers.[43] It stands to reason, therefore, that feelings of disgust may play an important role in judgments about HUDF acceptance.

1.1.3. Judgments about Risks and Benefits.

Two related variables that predict technology acceptance are perceptions of risks and benefits, which are typically studied in tandem. Risk and benefit perceptions tend to be inversely correlated; marketplace options judged as minimally risky tend to be simultaneously viewed as highly beneficial and *vice versa*.[44] Several studies detail the relationship between judgments of risks and benefits and consumer acceptance for emerging technologies such as GMOs and carbon capture and sequestration.[31,32,45] However, quantitative studies of judgments about risks and benefits in urine separation have been scant. In a recent study of Indian university students, attitudes toward human urine separation and HUDF were more positive when they learned that the human urine could be treated so as not to pose a health risk.[46] Another study of Dutch consumers found that risk and benefit perceptions were major predictors of acceptance of urine separating technologies.[47]

Within the context of fertilizers more broadly, research in the U.S. points to judgments of high risk for biosolid-based

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Table 1. Sample Characteristics[a]

	n	women (%)	mean age (SD)	low education (%)	medium education (%)	high education (%)
HUDF	513	51	44.7 (16.3)	22	36	42
Organic	471	48	44.5 (16.0)	25	38	37
Synthetic	516	50	45.3 (16.0)	24	36	42
Biosolids	508	48	45.0 (15.7)	23	39	37
TOTAL	2007	49	44.9 (15.9)	24	37	39

[a]Individual education levels were combined and categorized as low (no high school + some high school + graduated high school/GED), medium (medium education = some college + associate's degree), or high (bachelor's degree + graduate/professional degree); education was treated as a continuous variable in the regression analysis.

fertilizers.[43,48] The heightened attention on potential risks of biosolid application negatively impacted levels of acceptance generally, but judged risks decreased when biosolid application was geographically distant from participants' homes.[48] Therefore, acceptance of fertilizer application may also vary based on the type of use (e.g., crops for human consumption *vs* ornamental plants).

1.1.4. Perceived Naturalness. People tend to have an innate attachment to nature,[49] and a desire for natural *versus* processed or synthetic options influences judgments and decision-making in a variety of contexts from the protection of ecosystem services to food choice.[50,51] A reliance on the symbolism of naturalness can, however, lead to biased decisions, wherein identical alternatives—save for their biological or anthropogenic roots—are judged differently.[50] There is much work detailing the positive associations people have with "natural" foods. For example, organic food is often perceived as more natural and a healthier alternative to nonorganic certified foods. Similarly, labels misleading consumers by highlighting food ingredients as "natural" are both commonplace and are often conflated with perceptions of healthiness and may lead to suboptimal purchasing and consumption decisions.[52]

When it comes to emerging technologies in food and agriculture, perceptions of naturalness may play a pivotal role in acceptance.[53] Products perceived as unnatural have a marked reduction in acceptance levels, even if the product in question is more environmentally friendly than its "natural" alternative.[51] For example, meat produced through the growing of in vitro animal cells requires dramatically lower levels of energy, land use, and water than farm-raised meat.[54] However, these products are perceived as being less natural, leading to significantly lower levels of acceptability than conventional alternatives.[51]

Research on the perceived naturalness of novel nutrient recycling and fertilization methods is limited. In the context of conventional fertilizers, perceived naturalness may contribute to positive associations with organic fertilizer use and negative associations with agrobiotechnology and biosolid use.[29,43] The conventional option, synthetic fertilizer, is less natural than HUDF. Thus, even though nutrient recycling and the creation of HUDF will require extensive processing, the natural and more sustainable source of the nutrients—namely, human urine—may be a dominant factor in perceptions of naturalness and, ultimately, consumers' judgments about acceptability.

1.2. Aims of the Present Study. The primary aim of this research was to examine the degree to which judgments of risks and benefits, food disgust sensitivity, value orientations, and perceived naturalness influence U.S. food consumers' acceptance of fertilizers derived from human urine diversion and nutrient recycling, and that is used to grow foods for human consumption. Secondary aims of this research were to study U.S. food consumers' acceptance of HUDF when it is used to grow plants that are for nonedible uses and the relative acceptability of HUDF compared to other fertilizer types, namely, organic, synthetic, and biosolid-based. We chose these fertilizers for comparison because all three are widely used options. In addition, biosolids, such as HUDF, are a waste-based fertilizer, though they differ in content as biosolids are derived from household, industrial, and commercial wastewater, as opposed to solely human urine.

2. MATERIALS AND METHODS

2.1. Participants. Participants were United States residents recruited from a representative internet panel sourced by Qualtrics. We applied random quota sampling for assignment to one of four fertilizer treatments (see Section 2.2, below); likewise, we sought equal distributions across both gender and age (ages 18−29; 30−39; 40−49, 50−59; and 60+). The initial sample consisted of 5326 participants. After data cleaning, the total sample size dropped to 2007 participants distributed roughly equally across the treatments (Table 1); 3319 participants were removed from the data set because they did not give their informed consent ($n = 357$), did not complete ($n = 429$), or spent less than half the median time (2 min 56 s) on the instrument ($n = 1742$); because of the absence of variation (i.e., "straight-lining") in responses to questions on Likert scales ($n = 158$); because they failed a series of attention checks ($n = 609$); or because they began the survey after we reached the quota for participants ($n = 24$). The final sample sizes exceeded the sample size required for adequate statistical power.[55]

Across the four fertilizers studied, 49.2% of participants were women; the mean age of participants was 44.9 (SD = 15.9); and the median education level corresponded with self-reports of "some college", which was the midpoint of the included question about the education level (Table 1). These demographic characteristics mirror what constitutes the "average" American.[56]

2.2. Design. Participants responded to a survey (Figure S1) built around one of four different fertilizers: (1) HUDF; (2) organic fertilizer; (3) synthetic fertilizer; or (4) biosolid-based fertilizer. In reality, there may be overlap across some of these fertilizers depending upon how they are manufactured. However, given that consumer knowledge of fertilizers is low, because HUDF has not yet been the subject of regulatory certification, and because our study focuses on the source—urine diversion—of nutrients used in fertilizer manufacturing, we clearly differentiated these fertilizers in the information provided. The centerpiece of each survey was a short (1-page) primer about each participant's assigned fertilizer developed specifically for this research (Figures S4−S7). The primers provided participants with general information about why fertilizers are used, the basic content of each fertilizer, how

Table 2. ANOVA Results and Tukey's *Post-Hoc* Tests Comparing Fertilizer Types[1,2]

	HUDF		Organic		Synthetic		Biosolids				
	$\bar{x}$	SE	$\bar{x}$	SE	$\bar{x}$	SE	$\bar{x}$	SE	F	p	η^2
Perceived Naturalness	4.85[ab]	0.07	5.50[de]	0.07	2.74[f]	0.07	4.56	0.07	294.85	<0.0001	0.31
Risk											
human health	3.99[ab]	0.08	2.72[de]	0.07	4.73[f]	0.07	3.99	0.07	124.03	<0.0001	0.16
environmental health	3.74[ab]	0.08	2.90[de]	0.07	5.14[f]	0.07	3.93	0.08	195.91	<0.0001	0.22
Benefit											
human health	4.05[ab]	0.07	5.38[de]	0.06	3.50[f]	0.07	4.21	0.07	141.17	<0.0001	0.17
environmental health	4.38[ab]	0.07	5.47[de]	0.06	3.07[f]	0.07	4.37	0.07	208.12	<0.0001	0.24
Acceptability											
non-edible plants	5.19[ab]	0.07	5.67[de]	0.06	4.17[f]	0.07	5.19	0.07	90.21	<0.0001	0.12
animal consumption	4.37[ab]	0.08	5.34[de]	0.07	3.56[f]	0.08	4.48	0.07	93.31	<0.0001	0.12
home use	4.67[ab]	0.08	5.68[de]	0.06	3.78[f]	0.08	4.63	0.08	109.74	<0.0001	0.14
human consumption	3.95[ab]	0.08	5.55[de]	0.06	3.44[f]	0.08	4.06	0.08	142.03	<0.0001	0.18

[1]The Bonferroni corrected p-value required for significance was set at 0.005. [2]Key to *post-hoc* comparisons: [a]HUDF ≠ organic ($p \leq 0.001$). [b]HUDF ≠ synthetic ($p \leq 0.001$). [c]HUDF ≠ biosolid ($p \leq 0.005$). [d]Organic ≠ synthetic ($p \leq 0.001$). [e]Organic ≠ biosolid ($p \leq 0.001$). [f]Synthetic ≠ biosolid ($p \leq 0.001$).

nitrogen and phosphorus are sourced for each fertilizer, how each fertilizer is manufactured, and information about the corresponding benefits, risks, and uncertainties. This information was presented as text with an accompanying schematic that were reviewed for content and accuracy by water system designers, biophysical scientists, and agronomists from our broader team. The primers were immediately followed by an attention check question to determine whether participants could correctly identify the fertilizer they just learned about.

Identical survey instruments were shown to every participant, regardless of treatment group. The first question posed to participants asked, when you think about [this fertilizer], to what extent do you think of it as natural? Responses were collected on 7-point Likert scales from "not at all natural" to "extremely natural" (the midpoint was unlabeled). In the actual survey instrument, [this fertilizer] was replaced with the name of each participant's assigned fertilizer for all questions. Next, judgments about the risks and benefits of each fertilizer were measured using four questions across two contexts: people and environment. For judgments about risk, we asked for participants' level of agreement with two statements: [this fertilizer] will be harmful to my health and the health of my family and [this fertilizer] will be harmful to the environment (Cronbach's α = 0.89). For judgments about benefits, we created a scale (Cronbach's α = 0.88) based on participants' level of agreement with two statements: using [this fertilizer] will result in foods that are healthier for people and using [this fertilizer] will be healthy for the environment overall. Responses for all four questions were collected on 7-point Likert scales from "strongly disagree" to "strongly agree" (midpoint = "neither disagree nor agree").

We measured participants' level of acceptance regarding each fertilizer. Rather than overall acceptance, we subdivided and scaled (Cronbach's α = 0.89) questions according to four distinct end-uses. We asked for participants' level of agreement with four statements: it is acceptable to use [this fertilizer] to grow nonedible plants such as flowers; it is acceptable to use [this fertilizer] to grow fruits and vegetables that will be eaten by only animals; it is acceptable to use [this fertilizer] on the plants, trees, and grasses that grow around my home; and it is acceptable to use [this fertilizer] to grow fruits and vegetables for people to eat. Responses for all four questions were collected on 7-point Likert scales from "strongly disagree" to "strongly agree" (midpoint = "neither disagree nor agree").

Finally, we collected data on participants' level of food disgust sensitivity using an 8-item, prevalidated scale (Cronbach's α = 0.92),[57] and on their value orientations using a 12-item, prevalidated scale.[26] Regarding the former, respondents were asked to indicate how disgusting they perceived a series of items (e.g., hard cheese with the mold cut off and brown avocado pulp) or situations (e.g., eating with dirty silverware in a restaurant and discovering a snail in a salad) to be on 6-point Likert scales ranging from 1 = "Not disgusting at all" to 6 = "Extremely disgusting". Regarding the latter, we measured egoistic (four questions; Cronbach's α = 0.75), altruistic (four questions; Cronbach's α = 0.82), and biospheric value orientations (four questions; Cronbach's α = 0.90).

2.3. Analysis. We conducted analyses of variance with Tukey's *post-hoc* comparisons to detect differences between HUDF and other fertilizers across the main study variables outlined in Section 2.2: perceptions of naturalness, judgments of risks and benefits, and ratings of acceptability. For these analyses of variance, we treated risks and benefits, and acceptability variables separately. To lower the rate of type II errors due to multiple comparisons, we applied a Bonferroni correction; thus, the p-value required for significance in the ANOVA's and *post-hoc* tests was set at 0.005. We also conducted analyses of variance with Tukey's *post hoc* comparisons to understand distinctions between the various types of acceptance within the HUDF treatment group.

We also conducted exploratory linear hierarchical regressions to study the extent to which demographic characteristics (i.e., age, gender, and education), food disgust sensitivity, and perceptions of risks, benefits, and naturalness explained participants' acceptance of HUDF. We compared applications of HUDF where the product (food) was suitable for human consumption *versus* situations where HUDF would be applied to plants or crops intended for nonedible use. For simplicity, we combined all nonconsumptive uses of HUDF (i.e., applications on nonedible crops and plants, on crops consumed only by animals, and on nonedible plants around the home) into a single variable (Cronbach's α = 0.85).

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3. RESULTS AND DISCUSSION

3.1. Comparisons of Fertilizer Types. An ANOVA detected a significant main effect ($F_{(3,2003)}$ = 294.85, p < 0.001) between perceptions of naturalness across the four fertilizer types (Table 2). *Post-hoc* testing revealed significant differences between organic fertilizers and all other fertilizer types, wherein organic fertilizer was rated as the most natural. The opposite was the case for synthetic fertilizers; HUDF and biosolid-based fertilizers were perceived as significantly more natural than synthetic.

An ANOVA revealed a significant main effect between the four fertilizer types for judgments about risks (Table 2) to human ($F_{(3,2003)}$ = 124.03, p < 0.0001) and environmental ($F_{(3,2003)}$ = 195.91, p < 0.0001) health. *Post-hoc* testing for risk perceptions revealed a similar pattern; organic fertilizers were judged to be significantly less risky than the other three fertilizer types, and synthetic fertilizers were perceived as most risky. Participants rated HUDF and biosolids as similarly risky; there was no significant difference between these two fertilizers (p > 0.005).

Regarding perceptions of the benefits of each fertilizer type (Table 2), an ANOVA detected a significant main effect for benefits to human ($F_{(3,2003)}$ = 141.17, p < 0.0001) and environmental ($F_{(3,2003)}$ = 208.12, p < 0.000) health. Concerning between-fertilizer differences, synthetic was judged to be the least beneficial, with significant *post-hoc* differences between it and the other fertilizer types. Organic fertilizers were rated, on average, to be the most beneficial when compared with all other fertilizer types. As was the case for judgments about risk, participants rated biosolids and HUDF similarly beneficial.

Considering the acceptance variables (Table 2), an ANOVA detected significant main effects for all four fertilizer applications: for use on nonedible crops: ($F_{(3,2003)}$ = 90.21, p < 0.0001); for use on crops grown for animal consumption ($F_{(3,2003)}$ = 93.31, p < 0.0001); for use on plants around one's home ($F_{(3,2003)}$ = 109.74, p < 0.0001); *and* for use on crops intended for human consumption ($F_{(3,2003)}$ = 143.03, p < 0.0001). *Post-hoc* testing showed that, in all cases, participants were most accepting of organic fertilizer. Biosolids and HUDF were not significantly different from one another across any of the applications. Across all above ANOVAs, we generally observed medium to large effect sizes (Table 2).

Analyses of variance on the risk, benefit, naturalness, and acceptance variables across the four fertilizers revealed three main findings. First, organic fertilizers outperformed biosolid-based fertilizers, HUDF, and synthetic fertilizers on all variables. Participants perceived organic fertilizer, on average, to be the most beneficial and natural, the least risky, and were most accepting of it relative to the other fertilizer types. Second, our results also suggest that while synthetic fertilizers are the most widely used nationally, they were outperformed by all other fertilizer types across every variable (Table 2). Third, HUDF and biosolid-based fertilizers exhibit identical patterns of preference with respect to perceived naturalness and judgments about risks and benefits as it relates to both human and environment health (Table 2). The acceptability profiles for both HUDF and biosolid-based fertilizers were also identical when considering their application across four distinct end uses.

In light of these results, it is worth repeating that HUDF and biosolids-based fertilizers come from different forms of waste and differ in composition. Biosolids are the solid residual from centralized wastewater treatment facilities and are derived from combined household wastewater (including both feces and urine), industrial and commercial wastewater (which often includes fats, oils, heavy metals, and particulate chemicals), and in some cases particulate runoff with stormwater (including agricultural or urban landscape chemicals). Diverted human urine, in contrast, is captured in specialized toilets or urinals where it is separated from feces; likewise, if managed properly, this wastewater should be free from other wastes. While it is true that both HUDF and biosolids are treated to kill pathogens and remove residual pharmaceuticals to avoid accumulation in plants,[58,59] the production chain for HUDF is less energy intensive.[59] Despite these significant differences between HUDF and biosolids-based fertilizers, participants were not more accepting of one over the other. It may be the case, therefore, that the provision of comparative risk information to consumers could tip the acceptability balance in favor of HUDF.

3.2. Comparison of HUDF Applications. In terms of within-HUDF differences in acceptability ratings (Table 3), an ANOVA revealed a significant main effect ($F_{(3,2048)}$ = 43.60, p < 0.0001). *Post-hoc* testing detected significant differences between all acceptance comparisons; HUDF use for nonedible plants was most preferred, and HUDF use on crops for human consumption was least preferred. Mid-range levels of mean acceptability were observed for use of HUDF on vegetation around the home and on crops intended for only animal consumption. These differences in acceptability ratings of HUDF applications on fruits and vegetables for human consumption *versus* cases where HUDF is used on plants and crops are not intended for consumption by humans are in line with other research. For example, a study of Indian farmers found that they were generally accepting of HUDF but preferred it when people socially distal to them deployed it (*vs* people, such as family members, situated within their close social circles).[60] Similarly, a study of nanotechnology applications in food packaging *versus* in the foods themselves[34] demonstrated that consumers were more accepting of and exhibited a greater willingness to purchase the former over the latter.

Table 3. ANOVA Results and Tukey's *post-hoc* Tests Comparing the Acceptability of Different HUDF Applications[1]

	Acceptability	
	$\bar{x}$	SE
HUDF Application		
non-edible plants (NE)	5.19[abc]	0.07
animal consumption (AC)	4.37[de]	0.08
home use (HU)	4.67[f]	0.08
human consumption (HC)	3.95	0.08
F	43.60	
p	<0.0001	

[1]Key to *post-hoc* comparisons:[a]NE ≠ AC ($p \leq 0.001$). [b]NE ≠ HU ($p \leq 0.001$). [c]NE ≠ HC ($p \leq 0.001$). [d]AC ≠ HU ($p \leq 0.05$). [e]AC ≠ HC ($p \leq 0.001$). [f]HU ≠ HC ($p \leq 0.001$).

3.3. Predictors of HUDF Acceptance. The hierarchical exploratory regression examining consumers' acceptance of HUDF for use on crops intended for human consumption (table) had three steps. The first included demographic variables (age, gender, and education level). Gender was statistically significant with a small effect size (η^2 = 0.03); in that men were, on average, more accepting of HUDF use than women. The second step of the regression included the above-mentioned

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Table 4. Hierarchical Regression Results Depicting Variables That Predict Consumer Acceptance of Urine-Derived Fertilizers for Human Consumption[a]

	Step 1			Step 2			Step 3		
	β	95% CI	η^2	β	95% CI	η^2	β	95% CI	η^2
constant	3.52***	2.81; 4.23		3.89***	2.63; 5.14		1.02	−0.04; 2.08	
age	0.01	−0.01; 0.02	0.00	0.01	−0.01; 0.01	0.00	0.01	−0.00; 0.01	0.01
gender (0 = man)	−0.59***	−0.91; 0.28	0.03	−0.57***	−0.89; 0.26	0.03	−0.16	−0.37; 0.06	0.01
education	0.10	−0.01; 0.21	0.01	0.07	−0.04; 0.18	0.00	0.06	−0.02; 0.13	0.01
altruism				−0.08	−0.33; 0.18	0.00	−0.05	−0.21; 0.12	0.00
egoism				0.04	−0.13; 0.21	0.00	−0.02	−0.14; 0.09	0.00
biospherism				0.31**	0.07; 0.55	0.01	0.14	−0.02; 0.29	0.01
food disgust sensitivity				−0.31***	−0.48; 0.14	0.03	−0.00	−0.12; 0.11	0.00
risk							−0.26***	−0.35; −0.17	0.06
benefit							0.73***	0.63; 0.82	0.31
perceived naturalness							0.03	−0.06; 0.11	0.00
R^2		0.04			0.08			0.60	
F		4.94			5.20			69.08	
($df1$, $df2$)		(4, 507)			(8, 503)			(11, 500)	

[a] $*p < 0.05$, $**p < 0.01$, $***p < 0.001$.

Table 5. Hierarchical Regression Results Depicting Variables That Predict Consumer Acceptance of Urine-Derived Fertilizers for Nonhuman Consumption[a]

	Step 1			Step 2			Step 3		
	β	95% CI	η^2	β	95% CI	η^2	β	95% CI	η^2
constant	4.52***	3.94; 5.10		5.32***	4.31; 6.34		2.88***	1.95; 3.80	
age	−0.00	−0.01; 0.01	0.00	−0.00	−0.01; 0.01	0.00	0.00	−0.00; 0.01	0.00
gender (0 = man)	−0.44***	−0.70; −0.18	0.02	−0.43***	−0.69; −0.18	0.02	−0.09	−0.27; 0.10	0.00
education	0.10*	0.08; 0.19	0.01	0.05	−0.03; 0.14	0.00	0.03	−0.03; 0.09	0.00
altruism				0.12	−0.09; 0.32	0.00	0.10	−0.05; 0.25	0.00
egoism				−0.07	−0.21; 0.07	0.00	−0.11*	−0.21; 0.01	0.01
biospherism				0.16	−0.03; 0.35	0.01	0.03	−0.11; 0.10	0.00
food isgust Sensitivity				−0.36***	−0.50; −0.22	0.05	−0.12*	−0.22; −0.02	0.01
risk							−0.18***	−0.25; −0.10	0.04
benefit							0.40***	0.32; 0.49	0.16
perceived naturalness							0.21***	0.14; 0.28	0.06
R^2		0.04			0.10			0.55	
F		4.94			7.10			55.04	
($df1$, $df2$)		(4, 507)			(8, 503)			(11, 500)	

[a] $*p < 0.05$, $**p < 0.01$, $***p < 0.001$.

predictors and intuitive variables, specifically value orientations and food disgust sensitivity. Gender remained statistically significant with a small effect size ($\eta^2 = 0.03$); men continued to be, on average, more accepting than women. Biospherism and food disgust sensitivity were also both significant predictors of acceptance of HUDF use. Specifically, biospherism had a positive relationship to HUDF acceptance, and food disgust sensitivity was inversely related to acceptance.

The third step of the hierarchical regression included cognitive (i.e., system 2) variables, particularly judgments about HUDF's risks, benefits, and naturalness. We refer to these variables as "cognitive" because the 1-page primers about each fertilizer type included specific information for participants about its risks, benefits, and naturalness. Risks and benefits were highly correlated, inversely related, and highly significant (Table 4 and Figure S2). The effect size for risk was medium ($\eta^2 = 0.06$), while the effect size for benefit was large ($\eta^2 = 0.31$). Food disgust sensitivity, perceived naturalness, value orientations, and the battery of demographic factors no longer predicted acceptance of HUDF use on crops intended for human consumption.

The questions on consumers' acceptance of HUDF for use on crops not intended for human consumption were combined into a single, internally consistent (Cronbach's $\alpha = 0.85$) variable for a more straightforward analysis. The order of steps in this hierarchical regression (Table 5) was identical to those outlined above (Table 4).

Once again, in the third step, judgments about risks and benefits were both significant and inversely related predictors of acceptance and had small ($\eta^2_{\text{risk}} = 0.04$) and medium ($\eta^2_{\text{benefit}} = 0.16$) effect sizes. Perceived naturalness was a significant and positive predictor of acceptance with a low-medium effect size ($\eta^2 = 0.06$). Similar to risk perceptions, identifying with an egoistic value orientation was also a significant, inverse predictor of acceptance, with a small effect size ($\eta^2 = 0.01$). The same pattern was observed for food disgust sensitivity, which had a significant and negative predictive relationship with acceptance (with a small effect size; $\eta^2 = 0.01$). In the final step of the regression, the demographic factors did not predict acceptance of HUDF.

With respect to the specific variables that predict consumers' acceptance of HUDF in either context, our research suggests

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that the cognitive risk and benefit variables are central factors. Like other work related to urine separation and its associated technologies, benefit perceptions had a larger impact on acceptance than risk perceptions.[47] However, in designing our study, our goal was to go beyond just studying risks and benefits; hence, this was the reason we included measures of value orientations, perceived naturalness, and food disgust sensitivity in our survey and exploratory regressions.

We speculated based on other research[26] that identifying strongly with a biospheric value orientation would lead to greater support for HUDF. We did so because the way this fertilizer is manufactured—namely, urine diversion and nutrient recycling, the process behind which was clearly articulated to participants in this research (Figures S4−S7)—does not waste important and limited natural resources. We speculated about a similar mechanism with respect to perceived naturalness; products derived from natural ingredients (e.g., nutrients from a biological process in the case of HUDF) and processes (e.g., nutrient recycling in the case of HUDF) tend to be viewed more favorably than the same products developed through artificial or synthetic means.

As a counterweight to biospherism, we speculated that consumers who exhibit high levels of food disgust sensitivity would be less supportive of HUDF; the label "human urine-derived fertilizer" is more explicit about human waste as the source of nutrients (*vs* biosolids, which is a more ambiguous label even though the source is also human waste), and we know from prior research that most people view urine and feces as disgust-inducing.[27] As with the process of nutrient recycling outlined in the previous example, the source of nutrients was clearly articulated to participants (Figures S4−S7).

Regarding value orientations, perceived naturalness, and food disgust sensitivity, only perceived naturalness exhibited a significant predictive relationship to acceptance of HUDF and only when participants considered crops and vegetation for nonedible use. This was a surprising result and warrants further research. It may be that because naturalness was correlated with risks and benefits (Figure S2), when all were included in the regression models, this variable was rendered either marginally significant or insignificant. We expected the intuitive variables of food disgust sensitivity and value orientations to play a pivotal role in understanding of acceptance of HUDF. The variables, however, along with the included demographic variables, were either not robust or significant predictors when participants considered crops intended for human consumption or for nonedible use.

While it was the case that value orientations, disgust sensitivity, and demographic factors were significant predictors in initial model steps, they were either rendered insignificant when perceived risks and benefits were added to the hierarchical regression or they remained significant but with trivial effect sizes. Thus, it is safe to conclude that, in spite of differences in the significance of certain variables between the two modeled contexts (produce intended for edible *vs* non-edible use), the overarching conclusions about risk and benefit perceptions are fundamentally the same in that these are the two primary predictors of HUDF acceptance across both scenarios.

3.4. Practical Implications, Limitations, and Future Research. These results are positive from an applied perspective regarding the potential for the more widespread deployment of human urine diversion, nutrient recycling, and—ultimately—HUDF production and use. Synthetic fertilizers and biosolids are currently widely used in agriculture. In the current study, consumers' acceptance of HUDF is on par with biosolid-based fertilizers and outperforms synthetic fertilizers. This observation, coupled with the fact that a large proportion of consumers seem open to consuming foods produced with HUDF (Figure S3), leads us to believe there is a clear opportunity to begin to introduce HUDF to the marketplace.

However, we do not advocate taking this step without informing consumers. Some American consumers may have a general understanding of organic food and agriculture,[61] but in-depth knowledge about HUDF (and fertilizers in general) is quite low amongst the general population.[62,63] Therefore, informing consumers about how their food is grown and the impact of fertilizer production and use on environmental and human health will be essential.[63] In doing so, we advocate a research-based approach focusing on testing alternative messages and formats prior to their widespread release. We recommend this approach because raising awareness about a technology that science deems safe or beneficial can easily backfire.[64] In short, it should not be assumed that simply providing more information about HUDF will be adequate to positively influence consumer sentiment.

This study was not without limitations. For example, based on the lack of regulation regarding the certification of HUDF, we examined it as distinct from organics, synthetics, and biosolids. Going forward, it may be challenging to make this distinction. Changes to how nutrients from urine diversion are certified may lead them to be classified as a subset (or ingredient) of one or more of these other fertilizer categories; alternatively, HUDF could be classified as its own category of fertilizer. The unknown future pathway toward certification and classification should be accounted for future research about consumers' perceptions and communication about HUDF. Specifically, future research should test for interactions between HUDF and other classes of fertilizers. Future work may also focus on the role of prior knowledge about HUDF as a predictor of HUDF acceptance. Exploring a broader array of environmental and health risk perception contexts may provide more richness in understanding how risk contexts impact food consumer acceptance.

In the end, the results reported here should be accounted for by a wide range of researchers and practitioners working on research and development for HUDF deployment. Specifically, people working in agricultural supply chains, resource managers working to improve nutrient recycling efforts and wastewater systems, and sanitation practitioners considering new infrastructure could use this work to deepen their understanding of consumers' perceptions of HUDF. Because consumers' acceptance of HUDF seems strongly tied to intuitive perceptions of risks and benefits, an important next step is new research on risk communication efforts aimed at informing decisions about using and consuming agricultural products grown with HUDF.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.0c00576.

> Research design framework, correlation table of variables used in regressions, analysis and discussion of a "willingness to consume" variable assessing variance between fertilizer types, and schematics that participants received while the survey was conducted about each fertilizer type (PDF)

AUTHOR INFORMATION

Corresponding Author

Alex Segrè Cohen − *School for Environment and Sustainability, University of Michigan, Ann Arbor 48109-1382, Michigan, United States;* orcid.org/0000-0001-6387-2197; Email: alexcoh@umich.edu

Authors

Nancy G. Love − *Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor 48109-1382, Michigan, United States;* orcid.org/0000-0002-9184-2451

Kimmerly K. Nace − *Rich Earth Institute, Brattleboro 14260, Vermont, United States*

Joseph Árvai − *School for Environment and Sustainability and Erb Institute for Global Sustainable Enterprise Stephen M. Ross School of Business, University of Michigan, Ann Arbor 48109-1382, Michigan, United States; Decision Research, Eugene 97401, Oregon, United States*

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.est.0c00576

Notes

The authors declare no competing financial interest.

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