A meta-analysis on the effectiveness of food-waste reducing nudges

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ABSTRACT

Food waste is a global concern and is increasingly addressed by various policies and campaigns, especially in the consumption stage. Among these efforts, a promising instrument is gentle interventions based on nudges. To investigate whether and how a nudge works, we develop a theoretical framework and conduct a meta-analysis to synthesize empirical effects of nudges on reducing consumption food waste. The meta-analysis's summary effect size of cognitively-oriented nudges is a 0.27 SD (Cohen's *d*) reduction in food waste, and that of behaviorally-oriented ones is a 0.54 SD reduction. The effects of nudges are robust across sampled populations (i.e., U.S. vs. non-U.S. samples) but vary across settings (i.e., public vs. private). We further map nudge interventions to the driving factors of food waste behaviors and reveal potential research gaps in the literature. Based on these findings, we discuss implications for policy making to reduce food waste.

1. Introduction

Food losses and waste are a global issue with profound environmental impacts (Garrone et al., 2014; Moult et al., 2018; Secondi et al., 2015). While food losses often refer to the reduction of food matter and quality in the earlier stages of a food supply chain, food waste reflects losses in the later stages, as in retail and consumption (Cattaneo et al., 2021). Food waste in the consumption stage—the main focus of our later discussions—accounts for nearly 35% of total food losses and waste and contributes to 8–10% of global greenhouse gas emissions (Lipinski et al., 2013; UNEP, 2021). Moreover, food waste in consumption is associated with a long lifecycle and high accrued impacts (Gao et al., 2021), thus calling for requisite scholarly and practical attention. Various interventions have been used to combat food waste (Cattaneo et al., 2021; Delgado et al., 2021). For example, U.S. and some European governments raise public awareness of food waste via information provision. Chinese and Spanish governments ask food sellers to offer smaller food portions and provide "doggy bags" (see Table A1).

A popular effort to reduce food waste is a "nudge"—which is a voluntary, non-intrusive intervention that induces behavioral changes without economic incentives or mandates (Byerly et al., 2018; Earnhart & Ferraro, 2021; Thaler & Sunstein, 2008). Research shows that food waste is shaped by individual psychological, dietary, and habitual

factors, external influences from service providers and society, as well as these factors' complex interactions (Masotti et al., 2023; Quested et al., 2013; Stancu & Lähteenmäki, 2022; van Geffen et al., 2020). Such complex interactions may reduce the effectiveness of mandatory policies and educational campaigns. A nudge, however, might well serve as a useful policy alternative because food consumption pertains to the private sphere of one's life and depends on individual choices and volition (Jagau & Vyrastekova, 2017).

Despite its potential applicability, effectiveness of nudge-based interventions in reducing food waste is generally unclear. For example, providing information about the severity and consequences of food waste has been shown to be effective in some cases (Pinto et al., 2018; Whitehair et al., 2013) but ineffective in others (Ellison et al., 2019; Jagau & Vyrastekova, 2017). This inconsistency applies to nudge interventions in environmental and social policy domains broadly, thus leading to concerns about their effectiveness (Bryan et al., 2021; Chater & Loewenstein, 2022) and challenges to policymaking (Ferraro & Shukla, 2020).

Based on a meta-analytical approach, we present a synthesis of the effect of nudge interventions on reducing food waste. Building on previous categorization of nudge-based interventions (Cadario and Chandon, 2020), we develop a conceptual framework and related hypotheses, compare the effectiveness of cognitively-oriented and behaviorally-

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oriented nudges, and analyze contextual and methodological factors that affect the effectiveness of nudges. Influences from these characteristics are usually not identifiable in a single study conducted in one setting with one type of design (Morren & Grinstein, 2016). To further identify factors that have been little considered in nudge literature, we follow Varotto and Spagnolli's (2017) approach by mapping each type of nudge to the underlying driving factors of food waste.

Our research has important theoretical and policy implications. First, it contributes to the emerging discussion about the effectiveness of nudge interventions in reducing food waste (e.g., Reynolds et al., 2019; Stöckli et al., 2018; Tian et al., 2022) by showing the overall and relative effectiveness across types and subtypes of nudges. Different from an existing meta-analysis on the topic (Tian et al., 2022), we anchor our analysis to a theoretical framework and develop theory-driven hypotheses *ex-ante*. By separating nudge subtypes, we find a stronger effect of behaviorally-oriented than cognitively-oriented nudges in reducing waste. This distinction may not be obvious to policymakers, as cognitively-oriented nudges are predominantly used (Ellison et al., 2019; Stöckli et al., 2018).

Second, we show that reported policy effects are contingent, depending on how policies are implemented and effects are assessed. To reveal this, we investigate potential moderating roles of contextual and methodological factors that affect a reported nudge effect. Doing so permits enhanced understanding of seemingly heterogeneous effects across studies, and "could inform nuanced and dependable guidance to policymakers" (Bryan et al., 2021, p. 980).

Third, we show gaps and potential directions in the nudge literature by connecting nudge-based with determinant-based research on food waste. We reveal that studies on nudges have seldom targeted household food waste or consumers' dietary habits and routines. We further propose possible ways to facilitate research and policy design for household food waste reduction via nudges by borrowing insights from the determinant-based research.

2. Conceptual framework

2.1. Types of nudges for reducing food waste

Nudge is an umbrella term, referring to interventions that "modify the cues in the physical and/or social context" to support desired behaviors (Marchiori et al., 2017, p. 3). Nudge interventions are based on insights from psychology and behavioral economics, aiming to support behavioral changes without using economic incentives or prohibiting any options (Byerly et al., 2018; Earnhart & Ferraro, 2021; Marchiori et al., 2017).

Because nudges differ from one another in many aspects, a taxonomy is needed to assist further comparison and analysis. Following Cadario and Chandon's (2020, p. 466) taxonomy, nudges can be classified into three broad categories based on their underlying mechanisms: (1) *cognitively-oriented nudges* that intervene on what consumers know or believe; (2) *affectively-oriented nudges* that elicit consumers' feelings; and (3) *behaviorally-oriented nudges* that target directly others' behaviors "without necessarily changing what they know or how they feel." Few studies have examined affectively-oriented nudges in the context of *food waste reduction*. Therefore, we focus only on cognitively- and behaviorally-oriented nudges.

2.1.1. Cognitively-oriented nudges

Cognitively-oriented nudges elicit cognitive responses, focusing on changing people's attitudes or beliefs about food waste behavior. Two types of cognitively-oriented nudges have been identified: *prompts and information* and *kitchen diaries*.

Prompts and information seek to alter food consumption behaviors by increasing knowledge and awareness about the problem of wasting food. This type of nudge constitutes a sizable proportion of nudge-based interventions for food waste reduction, probably because of its low cost and ease of implementation (Ellison et al., 2019; Steg & Vlek, 2009; Stöckli et al., 2018). A typical research scenario of prompts and information entails displaying fliers, signs, posters, and table cards with prompt messages encouraging consumers to reduce food waste or using more elaborated information about issues and consequences of food waste and expected means to reduce waste (Whitehair et al., 2013).

Kitchen diaries require consumers to record the amount of food they waste daily and their specific plans to reduce waste. By reflecting on food-wasting behaviors and intentions to reduce waste, households are expected to recognize their behaviors and make changes more easily (Leverenz et al., 2019; Reid et al., 2009). Interestingly, though, Pelt et al. (2020) found, in collaboration with French local public authorities during a week-long intervention, that kitchen diaries did not reduce food waste. This paradoxical effect suggests that researchers should pay increased attention to consumers' mental activities when implementing food-reduction nudges. This issue is further illustrated in our discussion section.

2.1.2. Behaviorally-oriented nudges

Behaviorally-oriented nudges induce people to perform "good" behaviors by modifying the environment where choices and behaviors take place (Cadario & Chandon, 2020; Mertens et al., 2022). They do not necessarily change people's cognition or attitude, and sometimes even do not attract people's attention to the very existence of interventions. Common behaviorally-oriented nudges for food waste reduction include *providing smaller servings, altering plate attributes,* and *defaulting consumers to take leftovers* with them.

Smaller servings. Some scholars attribute food waste to retailers' increase of serving sizes and consumers' purchase of too much food (Jagau & Vyrastekova, 2017; Williamson et al., 2016). The issues could be directly addressed by smaller serving sizes, which are found effective in reducing food waste in settings of university dining facilities (Freedman & Brochado, 2010; Lorenz-Walther et al., 2019). Indirectly, contextual cues that could impel consumers to restrict their portion sizes spontaneously without mandates have also been investigated. Two strategies are *tray removal* and *smaller plate sizes*. *Tray removal*, or trayless dining, has been a notable trend in the food service industry over the past decade (Thiagarajah & Getty, 2013). Field experiments reveal that removing trays reduced food waste by 18% (Thiagarajah & Getty, 2013) to 35% (Kim & Morawski, 2012). A *smaller plate size*, as a visual reference, may lead to the perception of a larger amount of food served and thereby mitigate overserving problems due to the Delboeuf illusion (McClain et al., 2014). It may also cue consumption norms about the appropriate amount of food to consume, especially in buffet-style settings (Kallbekken & Sælen, 2013). Experimental evidence shows the effectiveness of a smaller plate size in reducing food waste (Kallbekken & Sælen, 2013).

Altering plate attributes. Sensory properties of tableware have been demonstrated to affect consumers' perceptions of food and their dining behaviors (Krishna & Morrin, 2008). For instance, Williamson et al. (2016) showed that plate materials influenced individuals' food consumption. Specifically, because consumers tend to associate disposable plates with food waste, a plate made of disposable materials would increase food waste. In addition, plate attributes—such as shape and color—also have been found to affect food consumption: compared with blue or white plates, placing food on red plates inhibited food consumption, resulting in more food waste (Bruno et al., 2013; Genschow et al., 2012).

Server-initiated leftover taking. Defaulting leftover taking—such as server-initiated leftover taking—may reduce food waste. When options to take leftovers are made convenient to consumers, they are more likely to be comfortable with such options, thus overcoming their inertia and status quo bias (Sunstein, 2017). Therefore, server-initiated leftover taking can mitigate consumers' sense of embarrassment or image concerns and minimize the inconvenience associated with asking for doggy bags. Further, default options signal the social norms in an environment,

which makes consumers regard the default as an implicit suggestion and behavioral prescription (Giaccherini et al., 2021; Sunstein, 2017).

2.2. Effects of nudges by type

Cognitively-oriented nudges involve improving what consumers "know" (Cadario & Chandon, 2020), which is useful when individuals lack sufficient knowledge about food waste. Previous research has observed an absence of awareness of environmental and social harm of food waste, as consumers are not likely to associate food waste with greenhouse gas emissions or other social impacts (Pearson et al., 2013; Watson & Meah, 2012). By highlighting environmental and social losses, cognitively-oriented nudges help consumers realize that food waste is environmentally harmful and socially undesirable. Attitudes and perceived social norms, in turn, influence subsequent behaviors (e.g., Ajzen, 1991; Stöckli et al., 2018). The discussion hence leads to the following hypothesis:

H₁: A cognitively-oriented nudge has a positive effect on reducing food waste.

Recent research has also cautioned that simply increasing knowledge of food waste and its consequences is insufficient to avoid food waste behavior (Stöckli et al., 2018). Consumers' decisions on selecting, eating, and wasting food are not based on extensive, deliberative thinking but rather on rapid, automatic thinking (Quested et al., 2013). Cohen and Babey (2012) have noted that eating behavior was less responsive to educational information than to contextual cues. Because behaviorally-oriented nudges work automatically, they might be more effective than cognitively-oriented nudges (Warren, 2017).

Furthermore, behaviorally-oriented nudges may be more effective than cognitively-oriented ones because of the lower cost associated with behavioral changes. Previous research has shown that cognitively-oriented nudges were only effective to the extent that they did not require much personal time or effort (Steg & Vlek, 2009). Maher and Burkhart (2017) found that, although university students were willing to reduce food waste, they needed external cues, motivators, and conditions to do so; therefore, reducing food waste had to be convenient and not involve too much additional time or effort. Behaviorally-oriented nudges usually do not pose an additional cost on food-saving behavior. Instead, they make food waste reduction convenient, for example, via using smaller plates or server-initiated taking of leftovers.

Finally, the broader literature on pro-environmental and healthy-eating behaviors has revealed a lower effect of cognitively-oriented nudges than behaviorally-oriented ones (Cadario & Chandon, 2020; Osbaldiston & Schott, 2012). Food saving behaviors are analogous to pro-environmental and healthy-eating behaviors in that they both have a marked attitude-behavior gap (Warren, 2017). These discussions all point to higher effectiveness of behaviorally-oriented nudges than cognitively-oriented ones in reducing consumer food waste. Thus, we posit the following hypotheses:

H₂: A behaviorally-oriented nudge has a positive effect on reducing food waste.

H₃: The effect of behaviorally-oriented nudges on food waste reduction is larger than that of cognitively-oriented nudges.

2.3. Influence of context and methodological variables

In addition to the type of nudges, the reported effect may also depend on contextual settings and research methods, including study setting, sample, design, and method used. The overall conceptual framework is presented in Fig. 1.

Study setting. One main distinction across studies is between public settings (e.g., hotels, cafeterias) and private settings (e.g., households). In public settings, a person's behavior is visible to others, making individuals more prone to follow social standards or normative influences (Burchell et al., 2013; Templeton et al., 2016). Because nudges, such as prompts and smaller portion sizes, raise public awareness regarding socially desired behaviors and social norms, they may be more effective when implemented in public than in private settings. In addition, there are more frequent interactions and greater social influence in public settings (Paluck & Shepherd, 2012; Warren, 2017), which can disseminate and reinforce the influence of a nudge. Taken together, we expect that the effect of a nudge will be higher in studies conducted in public than in private settings:

H₄: The effect of a nudge on reducing food waste is larger when the study is conducted in a public setting than in a private setting.

Sampled population. Prior research on healthy eating behavior has suggested that, when making food consumption decisions, U.S. consumers are more open and responsive to external than internal cues (Cadario & Chandon, 2020). Under this premise, we expect studies conducted in the U.S. to show a stronger effect of nudge interventions than those undertaken in other countries. We hence propose the following hypothesis:

H₅: The effect of a nudge on reducing food waste is larger in studies having used U.S. samples.

Study design. We compared studies that employed a pre-post design with a control group versus those that did not (e.g., a pre-post-only
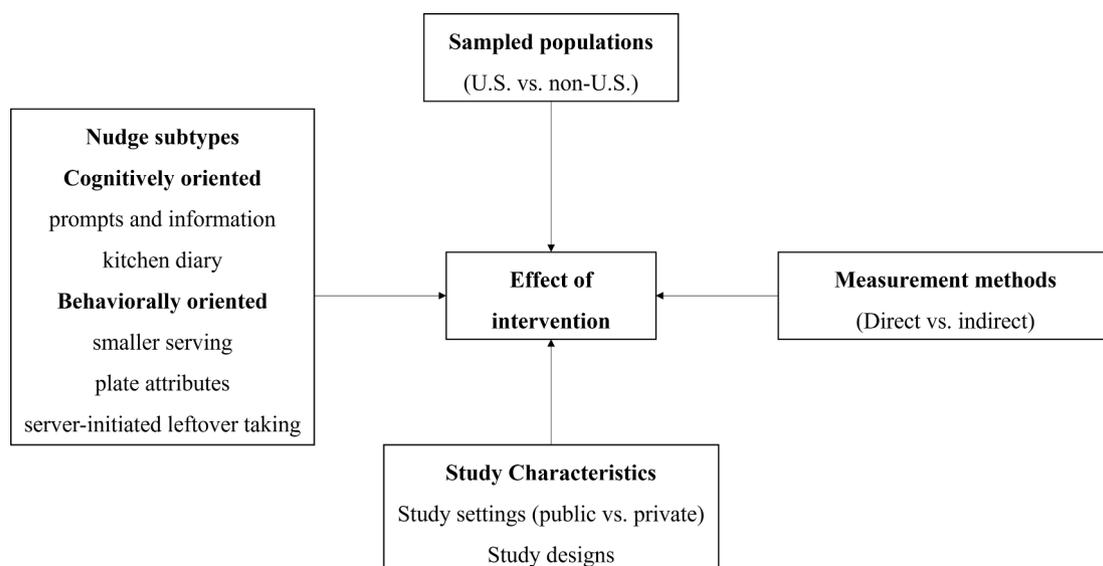

Fig. 1. Conceptual framework.

design). Compared with other types of study designs, the pre-post design with a control group is a tightly controlled ideal design (Abrahams & Matthies, 2018). Some meta-analyses have reported that pre-post designs with a control group have a more conservative estimate of effect than pre-post-only designs (Cole et al., 2021; Lundahl et al., 2006). Following this, we expect a smaller effect of a nudge reported in a pre-post design with a control group:

H_6: The reported effect of a nudge on reducing food waste is smaller in studies that employed a pre-post design with a control group.

Measurement method. In general, two approaches have been used to assess the amount of food waste. Some measured food waste by the weight of edible food waste left on plates, with the unit of analysis at individual/household-day level (e.g., Dolnicar et al., 2020; Hansen & Derdowski, 2020; Jagau & Vyrastekova, 2017; Pelt et al., 2020), hotel level (e.g., Kallbekken & Sælen, 2013), or day level (e.g., Ahmed et al., 2018; Pinto et al., 2018). Other scholars employed proxy measures of food waste, such as whether consumers took home leftovers (Giaccherini et al., 2021). Compared to direct measures, proxy measures lead to disparity in operationalization and conceptualization of a variable and therefore larger measurement error (Carver & Scheier, 2008). The difference between employing direct and proxy measures was exemplified in Ma et al.'s (2017) meta-analysis on gratitude and pro-sociality, showing that the association between gratitude and pro-sociality was weaker if proxy measures were employed. Thus, we propose the following hypothesis:

H_7: The reported effect of a nudge on food waste is higher when a study adopted a direct assessment rather than proxy measures of food waste.

3. Method

3.1. Search strategies

We searched for articles reporting nudge interventions to promote changes in food waste behaviors in scholarly journals on February 21, 2022. Keyword searches were conducted on the Web of Science and Google Scholar, using search strings based on the SPICE framework (Setting, Population, Intervention, Comparator, Evaluation) following Booth (2006). Presented in Table A2 are the search strings. References of six review articles (Aschemann-Witzel et al., 2015; Hebrok & Boks, 2017; Metcalfe et al., 2020; Reynolds et al., 2019; Schanes et al., 2018; Stöckli et al., 2018) were manually screened to determine whether there were additional relevant articles. Together, 677 articles were collected. Summarized in Table 1 are the nudge-based interventions for reducing food waste derived from those publications.

3.2. Inclusion and exclusion criteria

Shown in Fig. 2 is a flow diagram of the process undertaken to exclude articles following the "preferred reporting items for systematic reviews and meta-analyses" (PRISMA) guidelines (Moher et al., 2009). In the initial identification and screening phase, we removed duplicate entries (N = 9) and non-relevant articles (N = 548) from the search results. For example, articles focusing on food waste produced in stages other than in the consumption stage were excluded; work focusing on interventions for other food practices, such as healthy food intake and using food waste as an indirect measure of the practices (e.g, Lassen et al., 2014), was also omitted.

Among the remaining articles (N = 120), relevant ones were selected based on four criteria. First, research design was confined to experimental studies, which disentangle confounding factors and thus permit unbiased identification of the treatment effect. Second, selected studies implemented a nudge-based intervention rather than being undertaken in educational courses or offering economic incentives (Cadario & Chandon, 2020; Mertens et al., 2022). Third, only those investigations that measured actual food waste behavior—not self-reported behavior

Table 1
Details of the nudges used in prior studies.

Nudge	Study details
1. Cognitively-oriented nudges	
1.1 Prompts and information	
Whitehair et al. (2013)	• Place posters with messages on the amount of waste students have generated throughout facilities at a university dining hall.
Kallbekken & Sælen (2013)	• Place a sign encouraging guests to obtain food items more than once (e.g., "Visit our buffet many times. That's better than taking a lot once.").
Manomaivibool et al. (2016)	• Display informative materials to enhance students' perception of food waste, remind them to finish what they have ordered, and capture the attention of the food waste reduction campaign targets.
Jagau & Vyrastekova (2017)	• Display posters in a university restaurant: "Every person in The Netherlands wastes about 2–3 kg of food every week. Ask for a smaller portion."
Warren (2017)	• Display signs in the university dining halls (e.g., "Take what you'll eat").
Pinto et al. (2018)	• Prompts like "The bread you do not eat goes in the garbage"; staff advises users to ask for smaller portions.
Shaw et al. (2018)	• Prompts with information about the environmental and financial impact of food waste.
Stöckli et al. (2018)	• Prompts with information solely about the amount of food waste. Prompts with information *plus* descriptive norms (e. g., "Many people ask us to wrap their pizza leftovers.").
Dolnicar et al. (2020)	• Distribute flyers at hotel buffets: 2 (flyer types: reducing food waste appeal only vs. reducing food waste plus pro-environmental appeal) × 2 (rewards: present vs. absent).
Pelt et al. (2020)	• Distribute pamphlets on the consequences of food waste and the means to reduce food waste.
Van der Werf et al. (2021)	• Provide information on the quantity and average household value of food wasted, as well as information on environmental and social impacts of food wasting.
Giaccherini et al. (2021)	• Inform customers that asking for a doggy bag has become common.
1.2 Kitchen diary	
Pelt et al. (2020)	• Keep a kitchen diary and record food waste behavior.
2. Behaviorally-oriented nudges	
2.1 Smaller servings	
Freedman & Brochado (2010)	• Reduce the portion size from 88 g to 73 g, to 58 g, or to 44 g.
Kim & Morawski (2012)	• Remove trays in a university dining facility.
Thiagarajah & Getty (2013)	• Remove trays in a buffet-style university dining hall.
Wansink & van Ittersum (2013)	• Smaller (d = 21.0 cm) vs. larger plates (d = 26.5 cm).
Kallbekken & Sælen (2013)	• Reduce the plate size from 24 to 21 cm.
Lorenz-Walther et al. (2019)	• Serve smaller pieces of meat.
Richardson et al. (2021)	• Plate size and shape: larger round plates vs. smaller oval platters.
Werkman et al. (2022)	• Small serving (21.8 g) vs. large serving (43.6 g).
2.2 Other plate attributes	
Williamson et al. (2016)	• Plate material: disposable vs. permanent.
Hansen & Derdowski (2020)	• Plate color: white vs. colored plate.
Liu et al. (2022)	• Broad menu (i.e., three food size options displayed on the menu) vs. narrow menu (i.e., one food size option displayed on the menu).
2.3 Server-initiated leftover taking	
Giaccherini et al. (2021)	• Waiters initiated the delivery of the doggy bag.

or intentions—were included, given that intention and self-reported measures may exaggerate the true effect (Kormos & Gifford, 2014; Reynolds et al., 2019). Finally, although we contacted the authors of articles lacking the required statistical information to calculate effect sizes, this was not always successful. Therefore, only those
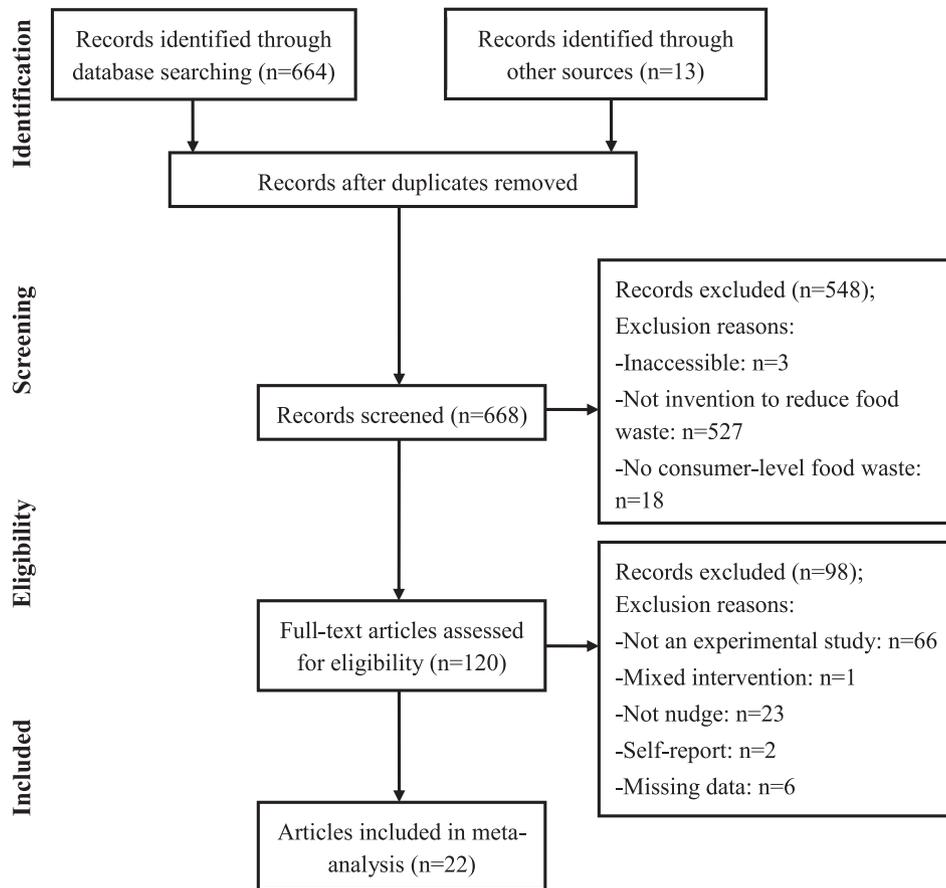
Fig. 2. PRISMA study selection flow chart.

investigations with computable effect sizes were included.

The final meta-analysis included 35 effect sizes from 22 articles. The number of observations in each study ranged from 11 to 9,680, with a median of 206. Details of the included studies are shown in Table A3 of the web appendix. Among the 35 studies reviewed, 25 were conducted in public settings and ten in private settings. Eight studies employed a pre-post-test with a control group, and 27 used other types of experimental designs. Ten investigations involved a U.S. sample; twenty-five collected data in other countries. Twenty-eight studies adopted direct measures, and seven utilized proxy measures of food waste.

3.3. Coding procedures

Included studies were coded by author, journal title, dependent measurement, tested nudge intervention, nudge type, sampled population, and treatment effect. Following previous research (Byerly et al., 2018; Cadario & Chandon 2020), our unit of analysis is a single intervention within a study. In other words, an investigation that tested multiple interventions simultaneously was separated into multiple entries.

3.4. Effect size calculation

The effect size of each study was then computed. The standardized mean difference between the treatment and control conditions (i.e., Cohen's d) was used as the measurement of effect size. This statistic was employed directly if it was reported in a study; otherwise, it was computed based on reported means, standard deviations, and sample sizes. For studies with a binary outcome, the odd's ratio was first computed and then converted into Cohen's d using formulas from

Borenstein et al. (2009). When effect sizes were not computable based on the reported information, we contacted the authors to obtain more information. The effect size was then computed based on the information or raw data from the authors.

A commonly unreported statistic in studies with a pre-post-test design is the correlation between the pre-test and post-test scores. Yet, this statistic should be considered in calculating the effect sizes to account for the interdependence of the pre-test and post-test scores (Cuijpers et al., 2017). We tried to contact the authors for this information but were not always successful. Thus, we followed Cuijpers et al. (2017) and used the correlation value reported in similar empirical investigations. Specifically, the correlation value of 0.76 reported by Visschers et al. (2020) was employed to calculate the standardized mean difference between studies with a pre-test and post-test design.

Heterogeneity of effect sizes is also important and often assessed based on Q and I^2 statistics. The Q statistic indicates whether heterogeneity in effects across studies is attributed to sampling errors. If those values are statistically non-significant, heterogeneity in effects is due to sampling errors, and thus a homogenous effect size is expected after correcting such errors. The I^2 statistic reveals the proportion of variances in effect sizes accounted for by extraneous factors (Conroy & Hagger, 2018). According to Higgins and Thompson's (2002) classification, percentage values of 25% ($I^2 = 25$), 50% ($I^2 = 50$), and 75% ($I^2 = 75$) imply low, medium, and high heterogeneity, respectively.

Another factor that may affect the calculation of effect sizes is publication bias. Publication bias refers to the problem where the likelihood of publishing a study is contingent on the outcome of the study (Borenstein et al., 2009). It arises for multiple reasons, such as negative findings being less likely to be submitted or published (Thornton & Lee, 2000). As a result, the effects in published studies may not reflect the

"true" effect, undermining the validity of meta-analysis. Thus, meta-analyses and interpretation of the effect size need to take publication bias into account (Palm-Forster et al., 2019).

Three methods were used to assess publication bias. First, we drew a "funnel" plot (Begg & Mazumdar, 1994), where each study was plotted by its effect size (x-axis) and the effect's standard error (y-axis). A funnel-shaped distribution of studies would suggest that the effect size was not driven by publication bias. Second, given that a "funnel" plot is a qualitative method relying on visual inspection, we also used Egger's test (Egger et al.,1997), which statistically tests distribution asymmetry. Third, we computed the fail-safe N, reflecting the number of nonsignificant outcomes needed to overturn the results (Rosenthal, 1979). The three methods are described in detail in the results section.

4. Results and discussion

To minimize the impact of very large or very small effect sizes on the overall effect size estimated, we identified the effect sizes outlying the 10th and the 90th percentile of the set of effect sizes (Spiegelhalter, 2005). Following previous meta-analytic studies (Conroy & Hagger, 2018), outliers identified were winsorized to the values of the 10th and 90th percentile of the set of effect sizes, respectively. Based on a random-effects model, we then calculated the summary effect by assigning a weight to the effect of each study according to the sample size (Borenstein et al., 2009). Finally, we assessed the heterogeneity of the effect sizes between subgroups and tested the possible publication bias.

4.1. Overall effect size

Meta-analysis results, reported in Table 2, showed that the overall average effect of nudges on reducing food waste was $d = 0.38$ (95% CI = [0.26, 0.49], z = 6.38, $p < 0.001$). The result of the Q test and I^2 index revealed substantial heterogeneity in effects across studies (Q-value = 161.72; $p < 0.001$; $I^2 = 78.98\%$). Assuming that the heterogeneity was not entirely random, we examined whether heterogeneity in the effects could be accounted for, at least in part, by nudge type and study-level methodological variables (Thompson & Sharp, 1999). Following Cole et al. (2021), a meta-analysis for each of the moderator subgroups was performed.

4.2. Moderator analysis

Nudge type. The first moderator of interest was the type of nudge. Both cognitively-oriented nudges ($d = 0.27$) and behaviorally-oriented nudges ($d = 0.54$) were effective, confirming H_1 and H_2. Compared with the cognitively-oriented nudges, behaviorally-oriented ones were significantly more effective ($Q = 5.35$, $p = 0.021$), supporting H_3. Similar to our results, Osbaldiston and Schott (2012) found that the effect of information-based nudges in encouraging pro-environmental behavior was modest ($g = 0.31$). Also, Cadario and Chandon (2020) observed a much smaller effect of cognitively- ($d = 0.12$) than behaviorally-oriented ($d = 0.39$) nudges in promoting healthy eating. The smaller effect of cognitively-oriented nudges revealed in our study was consistent with nudge effects on other behaviors.

Study setting. Compared with studies conducted in private settings ($d = 0.21$), those undertaken in public settings ($d = 0.44$) demonstrated greater effects of nudge interventions on reducing food waste ($Q = 4.59$; $p = 0.032$). Therefore, H_4 was confirmed. This more favorable effect of nudges in public situations is consistent with the view that publicity reinforces the influence of socially shared norms on individual behavior (Gamma et al., 2020; Green & Peloza, 2014).

Sampled population. The effect size was larger when nudge interventions were implemented in the U.S. ($d = 0.47$) than in other countries ($d = 0.33$), but this difference was not statistically significant ($Q = 1.39$; $p = 0.239$). Therefore, H_5 did not receive support. The weak influence of sampled populations on estimated outcomes suggests that samples from the U.S. are seemingly not fundamentally different from those in other countries. In other words, food-waste reducing nudges are likely applicable across cultural and regulatory contexts.

Study design. H_6 posited that the reported effect size of a nudge intervention depended on its study design, with a pre-post design including a control group yielding a smaller effect than other types of designs. Across published studies, those employing a pre-post design with a control group systematically reported lower effect sizes ($d = 0.21$) than those with other designs ($d = 0.42$; $Q = 4.43$; $p = 0.035$). A meta-analysis is incapable of correcting for hidden biases in studies (Ferraro & Agrawal, 2021). Because a pre-post design with a control group represents the most precise way to access the effect of an intervention (Abrahamse & Matthies, 2018), our analysis suggests that investigations employing other types of designs might, to some extent, exaggerate the effect.

Measurement method. Measurement methods were not found to be a

Table 2
Pooled effect size for each category of each moderator.

	K	d	95%CI		Two-tailed tests		
			Lci	Uci	Z	P	
Overall	35	0.38	0.26	0.49	6.38	0.000**	
Nudge types							
Cognitively oriented	21	0.27	0.16	0.37	4.90	0.000**	**Nudge types**: Q = 5.35; p = 0.021
- Prompts and information	17	0.28	0.16	0.40	4.69	0.000**	
- Kitchen diary	4	0.15	−0.17	0.46	0.92	0.360	
Behaviorally oriented	14	0.54	0.33	0.75	5.13	0.000**	
- Smaller servings	8	0.54	0.27	0.82	3.89	0.000**	
- Plate attributes	5	0.54	0.28	0.79	4.16	0.000**	
- Server-initiated leftover taking	1	0.48	−0.46	1.41	1.00	0.320	
Study settings							**Study settings**: Q = 4.59; p = 0.032
Public	25	0.44	0.30	0.58	6.12	0.000**	
Private	10	0.21	0.06	0.36	2.77	0.006**	
Sampled populations							**Sampled populations**: Q = 1.39; p = 0.239
Other countries	25	0.33	0.20	0.45	4.94	0.000**	
U.S.	10	0.47	0.27	0.67	4.56	0.000**	
Study designs							**Study designs**: Q = 4.43; p = 0.035
Other types	27	0.42	0.29	0.56	6.07	0.000**	
Pre-post design with a control group	8	0.21	0.07	0.36	2.92	0.004**	
Measurement methods							**Measurement methods**: Q = 0.07; p = 0.794
Direct assessment	28	0.39	0.27	0.50	6.64	0.000**	
Indirect assessment	7	0.34	0.07	0.62	2.41	0.016**	

significant moderator of nudge effects. Specifically, studies that assessed the amount of food waste by weighing the extent of food waste resulted in an effect ($d = 0.39$) not significantly larger than those using indirect measures ($d = 0.34$; $Q = 0.07$; $p = 0.794$). Thus, H_7 was not confirmed.

4.3. Publication bias

A funnel plot depicts the relationship between the effect size estimate and the standard error of the estimated effect. Standard error is inversely proportional to the sample size and reflects the precision of an estimate; a higher standard error entails lower estimate precision. The funnel plot in Fig. 3 shows studies with smaller standard errors—larger sample sizes and higher precision—clusters around the pooled estimate of the effect size, but those with larger standard errors—smaller sample sizes and lower precision—disperses broadly and identically on both sides of the pooled estimate of the effect size. The plot resembles a funnel shape, indicating the effects were unlikely to be distorted by publication bias.

The evidence from visual exploration was confirmed by Egger's test. In Egger's test, the standard normal deviation (SND, calculated as the effect size divided by the standard error) is regressed to the inverse of its standard error. The regression equation is:

$$SND = a + b \times \frac{1}{standard\,error} + \varepsilon$$

In the absence of publication bias, studies with a smaller sample size produce larger standard errors, and thus they will locate closer to zero on the x-axis. Although smaller studies can yield positive effect sizes, due to larger standard errors, the SND should be smaller and located closer to zero on the y-axis. If the effects reported in studies with smaller samples do not differ systematically from those with larger sample sizes, the regression line will run through the origin. Thus, a regression intercept that is not significantly different from zero indicates no publication bias (Egger et al., 1997). The significance of the regression intercept in our case was $p = 0.251$, showing little evidence of publication bias.

Finally, the fail-safe N was 1,527, meaning that more than 1,000 treatments with null effects were needed to reduce our estimated effect to nonsignificant. The fail-safe N was also larger than $5k + 10 = 120$ (k means the number of studies included), demonstrating that the meta-analysis results were robust concerning publication bias.
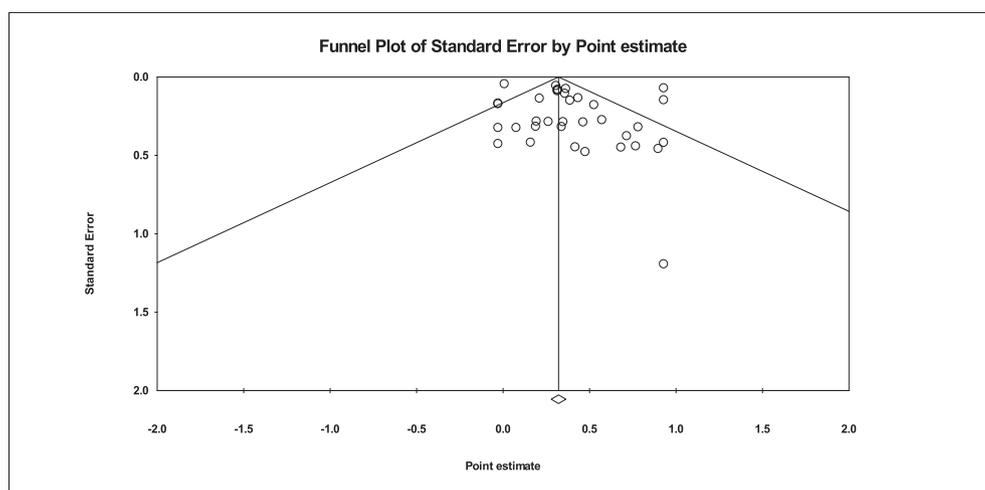
4.4. Linking nudge interventions to determinants of food waste

Nudge interventions could be linked to determinants of food waste to reveal current limitations in their application. We first reviewed the literature regarding driving factors that explained why people wasted food (e.g., Dhir et al., 2020; Hebrok & Boks, 2017; Masotti et al., 2023; Porpino, 2016; van Geffen et al., 2020) and found six categories. The six were psychological (e.g., awareness and knowledge, motivation and goals), socio-demographic (i.e., individual-related characteristics), dietary habits and routines (e.g., unplanned purchase, overpreparation of food), food-related (e.g., package, date labeling), service provider (e.g., characteristics of plates and tableware; leftover management practice), and societal and situational factors (e.g., availability and convenience of food for purchase). These factors are summarized in Table 3.

We then organized the studies included in the meta-analysis according to the context of a study (e.g., food services vs. households) and the categories of driving factors it addressed (e.g., psychological factors, service-provider factors). The factor that a given study had targeted was determined according to the reasoning and discussion of the author(s) of each study. For example, because Jagau and Vyrastekova (2017) described possible mechanisms of their manipulation as raising awareness, enriching knowledge, and inducing emotion, their intervention was linked to psycho-social drivers of food waste.

The findings are depicted in Fig. 4 and further illustrated in Table A4 of the web appendix. Most work had focused on reducing food waste in public contexts, and only a few centered on household food waste. Moreover, existing interventions addressed psycho-social (especially awareness and knowledge) and service-provider (e.g., color, shape, size, material of plates) factors much more than societal and situational factors and consumers' dietary habits and routines. There is a paucity of nudge research targeting food-related determinants and socio-demographic factors. Future research could develop more nudges in the context of household food waste and target food-related factors, dietary routines, and patterns.

5. Policy implications

We now interpret the overall effect of food waste reducing nudges. First, the estimated effect is compared with conventional interventions (e.g., economic incentives) and contextualized based on a back-of-the-envelope calculation to assess the substantive impact (i.e., carbon reduction). Next, we discuss implications of differential effects from

Fig. 3. Funnel plot of standard error by the point estimate *Notes*. Each dot represents a study. The y-axis is the standard error (standard error is the inverse of the estimate precision and inversely proportional to the sample size), and the x-axis is the estimated effect. The y-axis is reversed, thus studies with smaller standard errors are plotted at the top. If publication bias does *not* exist, studies with smaller standard errors—larger sample size and higher precision—will be distributed close to the pooled estimate of the effect, and those with larger standard errors—smaller sample size and lower precision—will be dispersed and distributed evenly on both sides of the average effect, thus forming a shape resembling a funnel. Conversely, if publication bias exists, the funnel shape will be skewed. Specifically, because publication bias is the lack of publication of smaller-sized studies with non-significant results, the lower left-hand area of the plot will be sparsely occupied or even missing (Thornton & Lee, 2000).

Table 3
A summary of determinants of food waste behaviors.

| Category	Characteristics within category
Psychological factors	**Awareness and knowledge**: awareness of food value and food waste and its consequences, knowledge about the negative impact of food waste **Motivation and goals**: being a good provider, being a role model for children, being concerned about health and food safety issues **Emotion**: positive/negative emotions connected to food waste (e.g., guilt) **Perceived behavioral control**: perceived ability to reduce food waste **Preference**: Desire for fresh food and "perfect" food **Personality traits**: conscientiousness
Socio-demographic factors	**Individual-related characteristics**: Age, life phase, income, gender, household size, household type, household constellation, lifestyle, nationality
Dietary habits and routines	**Planning**: existence of plans before shopping, planning skills **Shopping**: unnecessary and excessive purchases, impulsive buying **Storage**: knowledge, methods, and tools for food storage **Preparation and cooking**: over preparation of food, cooking skills **Leftover-handling**: habit of using leftovers
Food-related factors	**Package**: characteristics of the package (e.g., material, size, ease of emptying) **Date labeling**: expiration/sell-by date labeling **Food category**: Meat and dairy product are less likely to be wasted than vegetables
Service-provider factors	**Characteristics of plates and tableware**: Material, size, color, ease of emptying **Leftover management practice**: provision of doggy bags, monetary incentives (e.g., punishment (rewards) for (no) leftover) **Menu design**: Food waste reduction oriented vs. not food waste reduction oriented
Societal and situational factors	**Culture**: Consumers' country/culture of origin **Social norms around food waste**: Food wasting is commonly accepted or not accepted in the society **Availability and convenience of food for purchase**: Macro- and meso-forces that shape the time and energy people incur in food practices, as well as availability and convenience of food for purchase
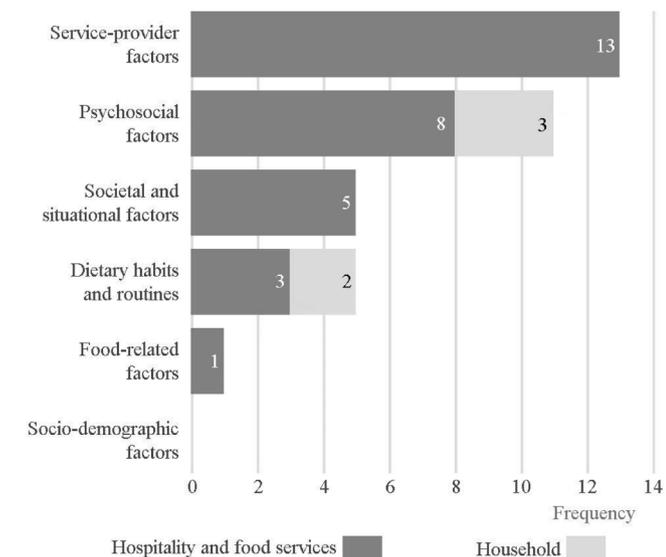
Fig. 4. Percentage of nudges that corresponds to each of the identified drivers of food waste behavior.

nudge subtypes and implementation contexts. Finally, we discuss how public and private entities could design nudge-based policies by taking insights from research on determinants of food waste.

5.1. Nudge as an instrument to reduce food waste

Results from our meta-analysis suggest a promising role of nudges in policy making to reduce food waste, with Cohen's $d = 0.38$. The efficacy revealed here is consistent with other nudge interventions in broader environmental protection domains, such as water and energy conservation (Bernedo et al., 2014; Henry et al., 2019). To make sense of the effect size, we can compare it with conventional incentive-based interventions. The average effect of financial incentives estimated by two previous studies (Dolnicar et al., 2020; Katare et al., 2019) was 0.40 with 95% CI = [0.24, 0.57]. Thus, the overall effectiveness of a nudge was at least not lower than economic incentives.

We then estimated the substantive impact of carbon emissions reduction resulting from implementing a nudge-based policy. Representing the standardized mean difference, Cohen's d of 0.38 infers that nudge-based interventions reduced food waste by 0.38 standard deviation (Cadario & Chandon, 2020). Based on the standard deviation of food waste reported by Richardson et al. (2021)—63 g per individual per meal—we estimated that, on average, nudge-based interventions reduced food waste by $0.38 \times 63 = 23.94$ g per individual per meal. To transform this into emission reduction, we relied on Li et al.'s (2021) lifecycle-based carbon emissions estimation of food waste. According to their estimation, the average carbon footprint caused by 1 kg of food waste was 2.19 kg of CO_2e. Thus, the average effect of nudges was equivalent to an estimated reduction of 0.05 $kgCO_2e$ per individual per meal or 54.75 kg CO_2e annually in reduced food waste. This effect is consequential, as a radical shift to a plant-based diet saves comparably 51 $kgCO_2e$ per individual annually (Wynes et al., 2018). However, the overall effect size should be interpreted with caution, owing to substantial heterogeneity in the effects across studies. Policy makers should also be aware of the differences in impacts generated by different types of nudges and implementation context.

5.2. More effective design for food waste reduction

When separating cognitively-oriented nudges from behaviorally-oriented ones, our findings showed that the former had a relatively smaller effect. Cognitively-oriented nudges should be carefully designed to improve their impact. According to cognitive psychology, vivid visual information can garner enhanced attention and is more persuasive (Costanzo et al., 1986). By comparing the height and weight of food waste to the height of the Empire State Building and the weight of two adult bulls, Ahmed et al. (2018) documented a large effect from an information nudge. In contrast, Jagau and Vyrastekova (2017) found a nonsignificant effect using mainly text. Accordingly, policy makers should embrace the use of information that translates clearly and pictorially individuals' food-related behaviors vis-à-vis food waste.

In addition, when implementing a cognitively-oriented nudge, the paradox or side effect should be noticed. For example, messages highlighting the amount of food wasted and its consequences may imply a descriptive norm of wasting food (Warren, 2017) and even induce self-defensive responses (Pelt et al., 2020). Underscoring the resources consumers help save (i.e., the amount of carbon footprint reduced) by eating all of their food at a meal or taking home leftovers may be an apt alternative to consider.

Although cognitively-oriented nudges are more commonly used in policies seeking to reduce food waste (Ellison et al., 2019; Stöckli et al., 2018), our results demonstrated that behaviorally-oriented nudges outperformed cognitively-oriented ones. Arguably, some behaviorally-oriented nudges might engender costs and be difficult to implement, such as providing smaller-size options and shifting to smaller plates. Nonetheless, our meta-analysis provides a basis with which

governments can conduct a cost-benefit analysis of a proposed policy to optimize the adoption of nudges for food waste reduction (Ferraro & Shukla, 2020).

5.3. Influence of implementation context

When considering the context in which a nudge is effective, we demonstrated that food waste-reducing nudges have similar effects across cultural and institutional contexts (i.e., U.S. and other countries). The effectiveness of nudges, however, varies between public and private settings. When implemented in a public setting (vs. a private setting), nudges have a greater effect. This implies potential synergy between nudge-based interventions and other policies applicable in the public setting. For example, the effectiveness of a nudge could be strengthened by activating self-image concerns or public accountability (Green & Peloza, 2014).

5.4. Household and design considerations

Finally, we turn to the context and design factors that are relevant yet less considered in current research on nudges. By comparing the context in which nudges are used, we observed limited research of nudges examining food waste in household contexts. But there appeared to be greater potential for policies to reduce food waste in household than in retail contexts (Goodman-Smith et al., 2020). Limited research in household contexts may be due to a lack of effective monitoring and quantification of food waste within households (Stöckli et al., 2018). Therefore, public and private entities are advised to develop monitoring and measurement methods (Cattaneo et al., 2021)—for example, smart bins—in efforts to overcome the obstacles of assessing household food waste.

Food-related triggers, such as labels and packages, are rarely considered in nudge interventions. Recent work has discussed the role of sell-by dates in reducing household food waste (Ananda et al., 2022; Yu & Jaenicke, 2021). Date labeling should be improved to be more understandable and less confusing to consumers; experimental studies would be helpful to explore effective designs of such label nudges. Also, public and private entities should devote efforts to interventions targeting food packages. For example, in response to the rise of single-person households, a novel way to reduce food waste is to bundle all ingredients in one package in supermarkets in a portion size for one person (Tsinghua University & UNEP, 2021).

Unlike one-time behavior, food-wasting behaviors are habitual and embedded in other suboptimal food-related practices, such as bulk purchasing, inaccurate forecasting, limited planning, and over-preparation (Mena et al., 2011; Stancu & Lähteenmäki, 2022; van Geffen et al., 2020). Thus, a promising solution is to help consumers overcome cognitive limitations and to improve their dietary knowledge, planning, and cooking skills (Min et al., 2021). Technology can empower such nudges. For example, mobile apps and smart refrigerators can make forecasting easier and more accurate and thus implicitly remind consumers of the desired behavior; smart bins can give real-time, personalized feedback that facilitates good food consumption habits (Altarriba et al., 2017; von Kameke & Fischer, 2018).

Last, public and private entities could consider nudge interventions targeting the household leftover-handling stage, such as making donations and circulation of soon-to-expire food easier. Combining social norms and motivational factors in this process may further enhance effectiveness (van Geffen et al., 2020). For instance, prompts encouraging parents to set a model for their children and messages comparing the amount of food waste of a household and its food-saving neighbor both create powerful motivations to reduce food waste (van Geffen et al., 2020).

6. Conclusion

The results of our meta-analysis revealed the overall effectiveness of nudges on reducing food waste, suggesting that they are a useful tool in combating the "wicked" food waste problem (Närvänen et al., 2020). The effects are stronger from behaviorally-oriented nudges than cognitively-oriented ones, reinforced when applied in public (vs. private) settings, and comparable between U.S. and other samples. Future policies would benefit from leveraging behaviorally-oriented nudges, presenting cognitively-oriented nudges more appealingly, considering possible synergies between nudge interventions and settings, and targeting households and food- and habit-related factors.

This study is subject to certain limitations that illuminate avenues for future research. First, although our estimation of the effect size was unlikely to be distorted by publication bias, the estimation was restricted to available studies. In our case, a large proportion of studies were conducted in student canteens and dining halls. Behavioral responses of student samples in these settings, often having more social interaction, may not reflect responses of the general population (Palm-Forster et al., 2019). The impact of nudge interventions is likely smaller when implemented in wider populations (Paluck & Shepherd, 2012; Warren, 2017).

As shown by the moderator analysis, the results showed high degrees of heterogeneity. Accordingly, the overall effect of nudges in reducing food waste should be viewed more conservatively. Two efforts may be useful when interpreting the effect of nudges. One is to assess the effectiveness of nudges for policy-relevancy by considering both effects and costs (Bernedo et al., 2014). The other is to sensitize researchers and practitioners to the influence of nudge subtype, setting, and study design in shaping the (reported) effect sizes.

Second, there is a lack of studies testing the longitudinal effects of nudge-based interventions. Although there is promising evidence that certain nudge influences can persist over time (Bernedo et al., 2014), the results are mixed (Marchiori et al., 2017). Thus, whether food waste reducing nudges can engender a long-term and habit-changing impact remains unclear. A fruitful avenue for future work would hence be exploring conditions and nudge subtypes that produce sustained effects. Future research could also leverage the ever-expanding literature (e.g., broader populations, longitudinal effects) to include more emerging studies.

Finally, under any categorization, an intervention could be ambiguously categorized in alternative ways(Osbaldiston & Schott, 2012) . Nudges that were categorized as cognitively oriented might well have also induced emotions (e.g., Jagau & Vyrastekova, 2017). Some nudges being categorized as behaviorally-oriented ones may also have an informational effect (Giaccherini et al., 2021). With a larger literature, scholars could explore alternative categorizations or exclude nudges with ambiguous categorization.

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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