Behavioral Lifestyle Intervention Program Using Mobile Application Improves Diet Quality in Adults With Prediabetes (D'LITE Study): A Randomized Controlled Trial

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ABSTRACT

Background Mobile health applications (mHealth apps) are increasingly being used in weight loss interventions. However, evidence on the effects of such interventions on diet quality and their correlation with weight loss is lacking.

Objective The objective of this study was to examine whether changes in the diet quality of adults with prediabetes followed the use of an mHealth-enabled lifestyle intervention, compared with those who did not, and whether these changes correlated with weight loss.

Design A secondary analysis of a 6-month randomized controlled trial Diabetes Lifestyle Intervention using Technology Empowerment (D'LITE) was conducted, with participants recruited from October 2017 to September 2019.

Participants/setting Community-dwelling adults (n = 148) in Singapore diagnosed with prediabetes and body mass index (BMI) ≥23 were included in this study.

Intervention Participants were randomized to receive either a 6-month mHealth-enabled lifestyle intervention program (diet and physical activity) or standard care dietary advice.

Main outcome measures Dietary data were collected in the form of 2-day food records at baseline, 3, and 6 months. Changes in Alternate Healthy Eating Index-2010 (AHEI-2010) scores and food groups (servings/day), calculated from the dietary data, and correlation between changes in AHEI-2010 and weight loss at 3 and 6 months, were examined.

Statistical Analyses Between-group comparisons of continuous variables and within-participants variation were performed using longitudinal mixed-effect models, intention-to-treat principles. The models included treatment groups, time (baseline, 3 months, and 6 months), and covariates (age, sex, and BMI), as well as the group × time interactions, as fixed variables and within-participant variation in outcome values as random variable. The random intercept for participants accounted for the dependence of repeated measures. A likelihood ratio test was also conducted to test random effect variance. Spearman correlation test was used to examine correlation between changes in AHEI-2010 scores and weight loss.

Results There was a significant improvement in overall diet quality as ascertained by the AHEI-2010, by 6.2 points (95% confidence interval [CI], 3.8−8.7; $P < 0.001$) in the intervention group as compared with the control. The participants in the intervention group had a significantly greater reduction in intake of sugar-sweetened beverages (SSB) by 0.5 servings/day (95% CI, −0.8, −0.2; $P < 0.001$) and sodium by 726 mg/day (95% CI, −983, −468; $P < .001$), compared with those receiving standard care. At 3 and 6 months, a significant decrease in SSB (0.8 servings/day; 0.7 servings/day, respectively) and sodium (297 mg/day; 296 mg/day, respectively) intakes were reported compared with baseline intakes. Small positive correlations ($r = 0.2$; $P < 0.05$) were observed between changes in AHEI-2010 scores from baseline and percentage weight loss at 3 and 6 months.

Conclusion For adults with prediabetes in Singapore, diet quality can be improved with an mHealth-enabled lifestyle intervention program. A small positive correlation exists between AHEI-2010 scores and weight loss.
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TYPE 2 DIABETES MELLITUS (T2DM) IS AN ONGOING global issue that requires urgent preventative public health efforts around the world.[1] Prediabetes is a condition that puts the individual at increased risk for the future development of T2DM.[2] The 3 criteria defining prediabetes are glycated hemoglobin A1c (HbA1c) 5.7% to 6.4% (39−47 mmol/mol), impaired fasting glucose of 100 mg/dL (5.6 mmol/L) to 125 mg/dL (6.9 mmol/L), or impaired glucose tolerance test showing 140 mg/dL (7.8 mmol/L) to 199 mg/dL (11.0 mmol/L).[3] A prospective cohort study found that amongst participants with prediabetes defined by the American Diabetes Association, women and men aged 45 years had a 14% and 9% 10-year risk of developing T2DM.[4] Like T2DM, the prevalence of prediabetes is rising at alarming rates globally.[5]

Prediabetes is reversible, and evidence continues to support the use of pragmatic lifestyle interventions as one of the most effective methods to reduce risk of progression to T2DM.[6] Weight loss is associated with lower risks of T2DM.[7] Diet quality, as ascertained by the alternate healthy eating index (AHEI), also has been shown to have an independent, inverse association with the risk of T2DM.[8] The measurement of diet quality with such indices provides an assessment of the diet in its entirety and allows the examination of the link between whole foods and certain nutrients and health status.[9] A systematic review of randomized controlled trials (RCTs) found that lifestyle interventions are associated with reduced risk of T2DM.[10] However, such lifestyle interventions delivered via face-to-face sessions or supervised exercise programs are often resource-intensive with high attrition rates, and limited by travel distances, time constraints, and cost.[11,12]

Another recent systematic review and meta-analysis of RCTs on the efficacy of mobile applications (apps) in supporting care of patients with T2DM found apps helpful in improving the control of HbA1c.[13] In another RCT, app users were found to have significantly greater improvements in diet quality and weight loss, as compared with controls.[14] Apps can be a useful mode of delivery of lifestyle interventions because they can facilitate regular communication with actual health care professionals (not artificial intelligence) and allow support to be delivered in a time-sensitive manner, while tailoring to individual needs.[15] A recent RCT showed that participants provided with a 6-month lifestyle intervention, delivered by a mobile health (mHealth) app, had a fivefold likelihood of achieving ≥5% weight loss compared with controls.[16] Another study identified a lack of time as a barrier, and presence of social support as an enabler toward dietary adherence in adults with T2DM.[17] The incorporation of a mobile health app (mHealth app) can provide real-time dietetic support without having the patient physically visit the dietitian's clinic.[18] The use of mHealth technology (including apps) will likely play an increasingly prominent role in the reversal of prediabetes and prevention of T2DM.[19]

Although emerging evidence supports the use of apps in facilitating weight loss,[20] their effect on diet quality in prediabetes is not well studied.[21] This gap was highlighted in a recent systematic review of efficacy of behavioral weight loss interventions for improving diet quality among adults that are overweight or obese.[22]

RESEARCH SNAPSHOT

Research Question: Can mHealth-enabled lifestyle intervention improve diet quality in adults with prediabetes who experienced significant intentional weight loss?

Key Findings: In this randomized controlled trial of 148 community-dwelling adults with prediabetes, participants that received the mHealth-enabled lifestyle intervention had statistically significant improvement in overall diet quality as ascertained by the Alternate Healthy Eating Index-2010 (AHEI-2010), by 6.2 points, reduction in sugar-sweetened beverages by 0.5 servings/day, and sodium by 726 mg/day, compared with those that did not. A small statistically significant positive correlation was observed between changes in AHEI-2010 scores from baseline and percentage weight loss at 3 and 6 months.

Only one pilot RCT using telenutrition weight loss intervention was identified, which also examined diet quality in men with chronic conditions, including prediabetes.[23] Furthermore, in weight loss trials, participants are often instructed to reduce food intake (to achieve caloric deficit),[24] and the possibility of a concomitant reduced intake of healthy foods is of concern. Therefore, it would be useful to examine how reduced food intake in weight loss trials affects diet quality. The objective of this study was to examine whether a behavioral interventional mHealth app, supported by dietitians, can improve diet quality in adults with prediabetes, as compared with usual care, and whether diet quality changes correlate with changes in percentage weight loss.

MATERIALS AND METHODS

Study Design and Setting

This study was a secondary analysis of the Diabetes Lifestyle Intervention using Technology Empowerment (D'LITE) trial, in which participants were recruited between October 2017 and September 2019, from primarily four health facilities that included government community polyclinics and hospital outpatient clinics in Singapore, by research staff. The D'LITE study is a parallel multicenter RCT to assess the effectiveness of a locally developed smartphone mHealth app compared with standard care dietary advice without mHealth app support in improving diabetes-related outcomes such as weight, biomarkers in adults with T2DM, and prediabetes.[25,26] Adults between 21 and 75 years of age with a diagnosis of prediabetes, with a Body Mass Index (BMI) more than or equivalent to 23 (according to the World Health Organization guidelines for Asians),[27] who could read and write in English, and who owned a smartphone with a data plan, were included in the current study. Exclusion criteria for the current study were known severe cognitive or psychological disabilities, heart failure, stage 4 and above kidney disease, untreated hypothyroidism, untreated depression, types 1 and 2 diabetes, pregnancy, untreated anemia, thalassemia, or other blood disorders. The study was conducted in accordance with the Declaration of

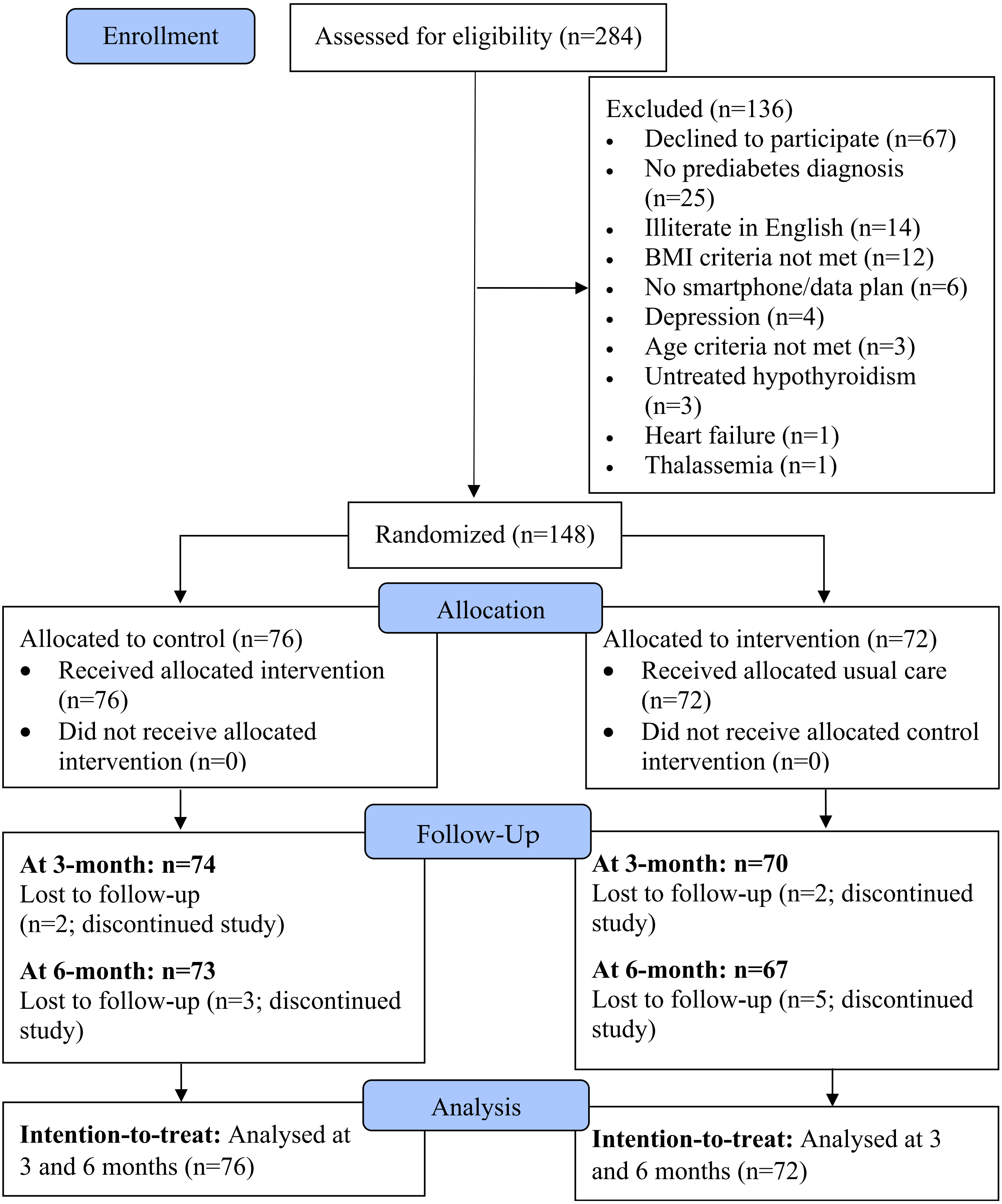

Figure 1. Flow chart of participant screening, recruitment, and randomization for the Diabetes Lifestyle Intervention using Technology Empowerment (D'LITE) trial, from October 2017 to September 2019.

Table 1. Baseline characteristics of 148 participants with prediabetes in the Diabetes Lifestyle Intervention using Technology Empowerment (D'LITE) study from October 2017 to September 2019 in Singapore

Characteristics	Control (n = 76)	Intervention (n = 72)
Age, y, mean (SD)	54.3 ± 9.9	51.9 ± 8.7
Sex, n (%)		
Male	46 (61)	43 (60)
Female	30 (40)	29 (40)
Ethnicity, n (%)		
Chinese	50 (66)	57 (79)
Malay	16 (21)	7 (10)
Indian	5 (7)	7 (10)
Others	5 (7)	1 (1)
Employment		
Paid employment (full/part-time)	53 (70)	53 (74)
Unemployed/retired/student	23 (30)	19 (26)
Weight, kg, mean ± SD	81.3 ± 12.5	82.5 ± 15.2
BMI,[a] mean ± SD	29.8 ± 3.9	29.8 ± 4.2
HbA1c, %, mean ± SD	6.06 ± 0.50	5.94 ± 0.48
Fasting blood glucose,[b] mg/dL, mean ± SD	112.3 ± 14.2	112 ± 15.3
Systolic blood pressure, mm Hg, mean ± SD	136 ± 17	137 ± 18
Diastolic blood pressure, mm Hg, mean ± SD	82 ± 11	83 ± 12
Total cholesterol,[c] mg/dL, mean ± SD	190.4. ± 39.9	199.7 ± 37.2
LDL cholesterol,[c] mg/dL, mean ± SD	109.8 ± 35.6	121.0 ± 32.9
HDL cholesterol,[c] mg/dL, mean ± SD	51.0 ± 11.2	49.5 ± 9.7
Triglycerides,[d] mg/dL, mean ± SD	155.9 ± 117.8	150.6 ± 73.5
Creatinine,[e] mg/dL, mean ± SD	0.9 ± 0.2	0.9 ± 0.2
Years of prediabetes, y	2.4 ± 2.6	1.9 ± 2.3
Co-morbidity, n (%)		
Hypertension	63 (83)	57 (79)
Hyperlipidemia	62 (82)	58 (81)
Energy intake,[f] kcal/day	1,868 ± 572	1,805 ± 433
Carbohydrate intake,[f] g/day	223 ± 79	214 ± 63
Protein intake,[f] g/day	79 ± 28	77 ± 22
Fat intake,[f] g/day	73 ± 25	72 ± 22
Sodium intake,[f] mg/day	3,375 ± 1,292	3,149 ± 1,137

[a]BMI = body mass index, calculated as kilograms per square meter. World Health Organization's BMI cutoff point for increased type 2 diabetes risk for Asian population ≥ 23

[b]To convert mg/dL fasting blood glucose to mmol/L, divide mg/dL by 18.

[c]To convert mg/dL total, low-density lipoprotein cholesterol and high-density lipoprotein cholesterol to mmol/L, multiply by 0.0259.

[d]To convert mg/dL triglyceride to mmol/L, multiply by 0.0113.

[e]To convert mg/dL creatinine to μmol/L, multiply by 88.4.

[f]Total dietary data available was n = 146 with n = 75 (control) and n = 71 (intervention) due to the lack of complete food diaries from two participants.

Helsinki and approved by the Singapore National Healthcare Group Domain Specific Review Board 2017/00397. Written informed consent was obtained from patients before enrollment into the study. This trial is registered with the Australian New Zealand Clinical Trials Registry (ACTRN12617001112358).

Randomization and Blinding

Stratified randomization of screened participants to intervention or control group was carried out using sealed opaque envelopes with a 1:1 allocation ratio, prepared by a third party not involved in the study and blinded to the study objectives, according to the

Table 2. Mean Alternate Healthy Index-2010 scores and food group (servings per day) and sodium (mg/day) of 146 participants with prediabetes in the Diabetes Lifestyle Intervention using Technology Empowerment (D'LITE) study from October 2017 to September 2019 in Singapore

Alternate Healthy Eating Index—2010 score	Control mean ± SD[a]	Intervention mean ± SD[a]
Total		
Baseline[b]	56.9 ± 11.1	58.0 ± 11.8
3 months[c]	56.2 ± 11.3	64.1 ± 10.1
6 months[d]	57.0 ± 11.1	64.5 ± 11.1
Vegetables		
Baseline[b]	4.3 ± 2.4	4.1 ± 1.8
3 months[c]	3.8 ± 2.3	4.2 ± 2.6
6 months[d]	4.1 ± 2.4	4.7 ± 2.5
Fruits		
Baseline[b]	2.2 ± 2.5	2.0 ± 2.1
3 months[c]	1.9 ± 2.0	2.0 ± 1.9
6 months[d]	1.9 ± 2.2	2.1 ± 2.1
Whole grains		
Baseline[b]	1.2 ± 1.9	1.4 ± 1.8
3 months[c]	1.2 ± 1.5	1.8 ± 2.0
6 months[d]	1.3 ± 1.9	1.7 ± 1.9
Sugar-sweetened beverages		
Baseline[b]	2.9 ± 4.1	2.8 ± 4.1
3 months[c]	3.9 ± 4.4	7.2 ± 3.6
6 months[d]	3.2 ± 4.1	6.4 ± 3.9
Nuts and legumes		
Baseline[b]	3.9 ± 4.2	4.7 ± 4.6
3 months[c]	3.4 ± 3.6	4.0 ± 3.9
6 months[d]	4.5 ± 4.3	4.2 ± 3.9
Red/processed meat		
Baseline[b]	6.0 ± 3.0	6.4 ± 3.0
3 months[c]	6.7 ± 2.8	7.1 ± 3.1
6 months[d]	5.7 ± 3.5	6.9 ± 3.0
Trans fat		
Baseline[b]	10.0 ± 0.2	10.0 ± 0.2
3 months[c]	9.9 ± 1.2	10.0 ± 0.2
6 months[d]	9.9 ± 0.3	10.0 ± 0
Eicosapentaenoic acid + Docosahexaenoic acid		
Baseline[b]	7.1 ± 4.3	7.1 ± 4.3
3 months[c]	6.6 ± 4.4	6.5 ± 4.6
6 months[d]	7.3 ± 4.2	6.1 ± 4.7
Polyunsaturated fatty acids		
Baseline[b]	5.0 ± 2.3	5.1 ± 2.3
3 months[c]	5.0 ± 2.4	5.4 ± 2.1

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Table 2. Mean Alternate Healthy Index-2010 scores and food group (servings per day) and sodium (mg/day) of 146 participants with prediabetes in the Diabetes Lifestyle Intervention using Technology Empowerment (D'LITE) study from October 2017 to September 2019 in Singapore (*continued*)

Alternate Healthy Eating Index—2010 score	Control mean ± SD[a]	Intervention mean ± SD[a]
6 months[d]	5.0 ± 2.6	5.7 ± 2.2
Sodium		
Baseline[b]	4.2 ± 3.3	4.5 ± 3.0
3 months[c]	4.2 ± 3.1	6.0 ± 2.8
6 months[d]	3.8 ± 3.0	6.6 ± 2.8
Alcohol		
Baseline[b]	10.0 ± 1.3	9.9 ± 0.6
3 months[c]	9.7 ± 1.3	10.0 ± 0.2
6 months[d]	9.9 ± 0.3	9.9 ± 0.4
Food groups (servings/day) and sodium (mg/day)	mean ± SD[a]	mean ± SD[a]
Total vegetables		
Baseline[b]	2.1 ± 1.4	2.0 ± 1.0
3 months[c]	1.9 ± 1.2	2.1 ± 1.5
6 months[d]	2.2 ± 1.3	2.4 ± 1.4
Total fruits		
Baseline[b]	0.9 ± 1.1	0.8 ± 1.0
3 months[c]	0.7 ± 0.8	0.8 ± 0.8
6 months[d]	0.8 ± 0.9	0.9 ± 0.9
Whole grains		
Baseline[b]	0.6 ± 1.6	0.7 ± 0.9
3 months[c]	0.6 ± 0.8	0.9 ± 1.0
6 months[d]	0.6 ± 0.9	0.8 ± 0.9
Nuts and legumes		
Baseline[b]	0.6 ± 0.9	0.6 ± 1.1
3 months[c]	0.5 ± 0.8	0.6 ± 1.0
6 months[d]	0.6 ± 1.0	0.5 ± 0.9
Fish		
Baseline[b]	0.5 ± 0.4	0.4 ± 0.4
3 months[c]	0.4 ± 0.4	0.3 ± 0.3
6 months[d]	0.6 ± 0.6	0.4 ± 0.4
Sugar-sweetened beverages		
Baseline[b]	1.5 ± 1.6	1.4 ± 1.5
3 months[c]	1.1 ± 1.1	0.3 ± 0.4
6 months[d]	1.2 ± 1.1	0.4 ± 0.6
Red and processed meats		
Baseline[b]	0.6 ± 0.6	0.6 ± 0.5
3 months[c]	0.6 ± 0.7	0.5 ± 0.5
6 months[d]	0.7 ± 0.7	0.5 ± 0.5
Sodium		
Baseline[b]	3,374 ± 1,293	3,149 ± 1,137

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Table 2. Mean Alternate Healthy Index-2010 scores and food group (servings per day) and sodium (mg/day) of 146 participants with prediabetes in the Diabetes Lifestyle Intervention using Technology Empowerment (D'LITE) study from October 2017 to September 2019 in Singapore (*continued*)

Alternate Healthy Eating Index—2010 score	Control mean ± SD[a]	Intervention mean ± SD[a]
3 months[c]	3,303 ± 1,224	2,590 ± 940
6 months[d]	3,477 ± 1,254	2,415 ± 913

[a]SD = standard deviation.
[b]Baseline dietary data available, n = 146; Control, n = 75; Intervention, n = 71.
[c]3 months' dietary data available, n = 142; Control, n = 74; Intervention, n = 68.
[d]6 months' dietary data available, n = 139; Control, n = 72; Intervention, n = 67.

Consolidated Standards of Reporting Trials statement.[28] These sealed envelopes were stratified by sex (male and female), age (<50 years old and ≥50 years old), and BMI (<27.5 and ≥27.5).

Control

Participants in the control group received standard face-to-face dietary advice based on healthy food plate meal-planning principles by a research dietitian at the baseline visit.[29] They were also supplied with a digital scale (Omron HN-289, Japan) for self-monitoring of their body weight twice per week. They were also advised to aim for 150 minutes of moderate-intensity physical activity per week.[30]

Behavioral mHealth Intervention

Participants randomized to the intervention (app) group also received the care described above for the control group. In addition, they were each provided with a glucometer (FreeStyle OptiumNeo, United Kingdom) as part of the app coaching program for weekly blood glucose monitoring. They were taught to download and use the Nutritionist Buddy Diabetes (nBuddy Diabetes)[31] —a diet, physical activity, and blood glucose monitoring app, designed by principal investigator S. L. L. and created by HeartVoice using the behavioral treatment strategies and Obesity-Related Behavioral Intervention Trials model for behavioral treatment as a framework for translating behavioral science discoveries into treatments.[32] During the study period, individualized health coaching through the app was provided by the research dietitian based on the participants' app input (eg, food intake, blood glucose, weight, physical activity), as accessed via the app's dashboard. Participants in the intervention group were offered daily (on weekdays only) coaching during the clinic's 8 hours of operation. Coaches were available during this 8-hour period and responded within 24 hours of a given workday. In-depth details on the app features and study protocol and cohort have been previously published.[25,26]

Assessment of Diet Quality

Diet quality was ascertained using the Alternate Healthy Eating Index-2010 (AHEI-2010).[33] The AHEI-2010 is based on foods and nutrients that are predictive of chronic disease risk. In brief, it consists of 11 components: 6 adequacy components (vegetables, fruit, whole grains, nuts and legumes, eicosapentaenoic acid + docosahexaenoic acid, and polyunsaturated fatty acids), for which higher intakes are associated with lower chronic disease risk, 1 component for which moderate intake is better (alcohol), and 4 components (sugar-sweetened beverages [SSB] and fruit juice, red and processed meat, trans fats, and sodium) for which lower intakes are associated with lower chronic disease risk. Each component was scored on a 0- to 10-point scale and scores were summed to obtain the total AHEI-2010 score, ranging from 0 to 110 (nonadherence to perfect adherence). For this analysis, dietary data from the 2-day food diaries, at baseline, 3-, and 6-month visits were included. Study participants were instructed by a research dietitian on how to record type of food and beverage consumed as well as amount consumed. All participants completed a 2-day food diary at enrollment and the subsequent visits, ie, 3- and 6-month visits, reflective of usual intakes of a weekday and weekend. Food groups—total vegetables, total fruit, whole grains, nuts and legumes, fish, SSB, red and processed meat (servings/day)—and sodium (mg/d) were also analyzed. Dietary intake was analyzed at baseline, 3- and 6-month visits via a local nutrient analysis platform, Nutritionist Buddy Version 4.5.6.1,[31] which comprises information from Singapore Energy and Nutrient Composition of Food,[34] Malaysian Food Composition,[35] and United States Department of Agriculture food databases,[36] along with nutritional panels from food packaging. Recipes' nutrient analyses were performed for composite foods that were not available, such as home-cooked recipes.

Mobile App Utilization

In addition, app utilization data of intervention participants during the 6-month intervention period were collected from the nBuddy mobile app dashboard. For this study, overall app utilization was defined as the number of days participants engaged in one or more features of the app over the intervention period. The 2-way interactions between the participants and dietitians were also recorded in the app's chat log and recorded—a successful interaction day was defined as a comment or question from the participant, or an in-app text response from a participant regarding a comment or question from the dietitian within the next working day.

Other Measures

Body weight was measured using a digital scale (Omron HN-289, Japan). Height was measured using stadiometers (Seca) available at the primary care clinics. Height and weight were measured without shoes and in light clothing; three

Table 3. Mixed-model results adjusted for age, sex, and body mass index, group × time interaction for changes in diet quality at 3 and 6 months of 146 participants with prediabetes in the Diabetes Lifestyle Intervention using Technology Empowerment (D'LITE) study from October 2017 to September 2019 in Singapore, using intention-to-treat principles

	Alternate Healthy Eating Index—2010						
	Total score	Vegetables	Fruits	Whole grains	SSB[a]	Nuts and legumes	Red and processed meat
	Estimates (95% CI), *P*-value						
Fixed effect (between participant effect)							
Control	Ref	Ref	Ref	Ref	Ref	Ref	ref
Intervention	6.2 (3.8, 8.7), $P < 0.001$	0.2 (−0.3, 0.8), $P = 0.39$	0.3 (−0.2, 0.8), $P = 0.21$	0.4 (0, 0.9), $P = 0.08$	2.2 (1.1, 3.2), $P < 0.001$	0.5 (−0.3, 1.4), $P = 0.23$	0.7 (0, 1.4), $P = 0.07$
Time							
Baseline	Ref	Ref	Ref	Ref	Ref	Ref	Ref
3 months	2.5 (0.3, 4.7), $P = 0.03$	−0.2 (−0.7, 0.2), $P = 0.32$	−0.2 (−0.6, 0.2), $P = 0.39$	0.2 (−0.2, 0.5), $P = 0.32$	2.6 (1.8, 3.3) $P < 0.001$	−0.7 (−1.6, 0.2), $P = 0.12$	0.7 (0.1, 1.3), $P = 0.03$
6 months	3.1 (0.8, 5.3), $P = 0.01$	0.2 (−0.2, 0.7), $P = 0.32$	−0.1 (−0.5, 0.3), $P = 0.67$	0.2 (−0.1, 0.5), $P = 0.26$	1.9 (1.1, 2.6) $P < 0.001$	0 (−0.9, 0.9), $P = 0.97$	0 (−0.6, 0.7), $P = 0.87$
Random effect (within participant effect)							
Variance (SD[b])	23.5 (4.9)	1.5 (1.2)	0.9 (1.0)	1.3 (1.1)	5.8 (2.4)	2.0 (1.4)	2.1 (1.5)
Likelihood ratio test	$\chi^2 = 15.5$, $P < 0.001$	$\chi^2 = 26.8$, $P < 0.001$	$\chi^2 = 22.4$, $P < 0.001$	$\chi^2 = 58.4$, $P < 0.001$	$\chi^2 = 48.0$, $P < 0.001$	$\chi^2 = 6.1$, $P = 0.01$	$\chi^2 = 20.8$, $P < 0.001$
Group × time interaction	$\chi^2 = 11.9$, $P = 0.003$	$\chi^2 = 3.1$, $P = 0.21$	$\chi^2 = 1.3$, $P = 0.51$	$\chi^2 = 1.1$, $P = 0.59$	$\chi^2 = 26.9$, $P < 0.001$	$\chi^2 = 1.9$, $P = 0.38$	$\chi^2 = 2.3$, $P = 0.31$

	Alternate Healthy Eating Index—2010				
	Trans fat	Eicosapentaenoic acid + Docosahexaenoic acid	Polyunsaturated fatty acids	Sodium	Alcohol
	Estimates (95% CI), *P*-value				
Fixed effect (between-participant effect)					
Control	Ref	Ref	Ref	Ref	Ref
Intervention	0 (0, 0.1), $P = 0.44$	−0.3 (−1.2, 0.6), $P = 0.52$	0.4 (−0.1, 0.9), $P = 0.16$	1.7 (1.1, 2.4) $P < 0.001$	0 (−0.2, 0.2), $P = 0.79$
Time					
Baseline	Ref	Ref	Ref	Ref	Ref

(*continued on next page*)

Table 3. Mixed-model results adjusted for age, sex, and body mass index, group × time interaction for changes in diet quality at 3 and 6 months of 146 participants with prediabetes in the Diabetes Lifestyle Intervention using Technology Empowerment (D'LITE) study from October 2017 to September 2019 in Singapore, using intention-to-treat principles (*continued*)

	Alternate Healthy Eating Index—2010				
	Trans fat	Eicosapentaenoic acid + Docosahexaenoic acid	Polyunsaturated fatty acids	Sodium	Alcohol
	Estimates (95% CI), *P*-value				
3 months	−0.1 (−0.2, 0.1), $P = 0.32$	−0.6 (−1.6, 0.4), $P = 0.24$	0.1 (−0.4, 0.6), $P = 0.63$	0.7 (0.2, 1.3) $P = 0.01$	−0.1 (−0.3, 0.1), $P = 0.18$
6 months	−0.1 (−0.2, 0.1), $P = 0.32$	−0.3 (−1.4, 0.6), $P = 0.46$	0.3 (−0.2, 0.8), $P = 0.19$	0.8 (0.2, 1.4), $P = 0.01$	0 (−0.2, 0.2), $P = 0.84$
Random effect (within-participant effect)					
Variance (SD[b])	0 (0)	0.9 (1.0)	1.0 (1.0)	1.9 (1.4)	0.1 (0.3)
Likelihood ratio test	$\chi^2 = 0$, $P = 1.00$	$\chi^2 = 0.94$, $P = 0.17$	$\chi^2 = 12.7$, $P < 0.001$	$\chi^2 = 19.1$, $P < 0.001$	$\chi^2 = 7.0$, $P = 0.004$
Group × Time interaction	$\chi^2 = 2.5$, $P = 0.29$	$\chi^2 = 1.6$, $P = 0.46$	$\chi^2 = 1.9$, $P = 0.38$	$\chi^2 = 15.8$, $P < 0.001$	$\chi^2 = 4.41$, $P = 0.11$

	Servings per day							Mg/day
	Vegetables	Fruits	Whole grains	Nuts and Legumes	Fish	SSB	Red and processed meat	Sodium
	Estimates (95% CI), *P*-value							
Fixed effect (between-participant effect) rowhead								
Control	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
Intervention	0.1 (−0.2, 0.4), $P = 0.38$	0.1 (−0.1, 0.3), $P = 0.23$	0.2 (−0.1, 0.4), $P = 0.18$	0.1 (−0.1, 0.3), $P = 0.52$	−0.1 (−0.2, 0), $P = 0.05$	−0.5 (−0.8, −0.2), $P < 0.001$	−0.1 (−0.3, 0), $P = 0.04$	−726 (−983, −468), $P < 0.001$
Time								
Baseline	Ref	Ref	Ref	Ref	Ref	Ref	Ref	ref
3 months	−0.1 (−0.3, 0.2), $P = 0.55$	−0.1 (−0.2, 0.1) $P = 0.32$	1.1 (−0.1, 0.2), $P = 0.48$	−0.1 (−0.2, 0.1), $P = 0.40$	−0.1 (−0.2, 0), $P = 0.20$	−0.8 (−0.9, −0.6), $P < 0.001$	−0.1 (−0.2, 0), $P = 0.17$	−297 (−527, −66), $P = 0.01$
6 months	0.2 (0, 0.5) $P = 0.10$	0 (−0.2, 0.1), $P = 0.68$	0.1 (−0.1, 0.2), $P = 0.52$	−0.1 (−0.2, 0.1), $P = 0.40$	0.1, (0, 0.2), $P = 0.19$	−0.7 (−0.8, −0.5), $P < 0.001$	0 (−0.1, 0.1), $P = 0.71$	−296 (−526, −66) $P = 0.01$
Random effect (within-participant effect) rowhead								
Variance (SD[b])	0.5 (0.3, 0.7)	0.2 (0.2)	0.4 (0.6)	0.2 (0.5)	0 (0)	0.4 (0.6)	0.1 (0.2)	263,568 (513)

(*continued on next page*)

Table 3. Mixed-model results adjusted for age, sex, and body mass index, group × time interaction for changes in diet quality at 3 and 6 months of 146 participants with prediabetes in the Diabetes Lifestyle Intervention using Technology Empowerment (D'LITE) study from October 2017 to September 2019 in Singapore, using intention-to-treat principles (*continued*)

	Servings per day							Mg/day
	Vegetables	Fruits	Whole grains	Nuts and Legumes	Fish	SSB	Red and processed meat	Sodium
	Estimates (95% CI), *P*-value							
$\chi^2 = 36.6$, $P < 0.001$		$\chi^2 = 34.2$, $P < 0.001$	$\chi^2 = 63.5$, $P < 0.001$	$\chi^2 = 37.8$, $P < 0.001$	$\chi^2 = 2.3$, $P = 0.06$	$\chi^2 = 50.8$, $P < 0.001$	$\chi^2 = 12.6$, $P < 0.001$	$\chi^2 = 17.3$, $P < 0.001$
Group × Time interaction	$\chi^2 = 2.7$, $P = 0.26$	$\chi^2 = 1.5$, $P = 0.47$	$\chi^2 = 2.1$, $P = 0.35$	$\chi^2 = 2.9$, $P = 0.24$	$\chi^2 = 4.00$, $P = 0.14$	$\chi^2 = 16.5$, $P < 0.001$	$\chi^2 = 2.7$, $P = 0.27$	$\chi^2 = 13.6$, $P = 0.001$

[a]SSB = Sugar-sweetened beverages.
[b]SD = Standard deviation.

readings were taken, and the average of the 3 readings was recorded. Hemoglobin A1c, Fasting Blood Glucose (FBG), blood pressure, serum lipids, creatinine, and co-morbidities were also collected to describe the baseline metabolic profile of the cohort. Venous blood samples were collected from participants after an 8- to 12-hour overnight fast and processed at College of American Pathologist accredited laboratories in Singapore (National University Hospital Department of Laboratory Medicine or National Healthcare Group Diagnostics). Plasma glucose and HbA1c were determined by the hexokinase method, using photometric assay and high-performance liquid chromatography, respectively. Serum lipids and creatinine were measured using enzymatic colorimetric assay. Co-morbidity (hypertension and hyperlipidemia) were collected from participants' electronic medical records once at baseline. Data on participants' characteristics such as age, sex, and ethnicity were also collected once at baseline as part of the data collection form, where participants self-reported on age, sex, and ethnicity. All data were collected at one of the four health facilities during participants' visits.

Statistical Analysis

Sample size was previously calculated with 90% power at 5% significance level (two-sided) and 10% attrition rate, based on the assumption of a moderate Cohen effect size of at least 0.5 for the difference in weight loss between groups at 6 months. Data analyses were performed using STATA version 17 (StataCorp)[37] and SPSS version 28 (SPSS Inc, Chicago, IL).[38] Results with continuous variables were expressed as mean and SD, and categorical data were expressed as frequencies and percentages. Normality tests (Kolmogorov–Smirnov and Shapiro–Wilk) were performed for variables at all time-points. Between-group (fixed effect) comparisons of continuous variables and within-participants variation (random effect) were performed using longitudinal mixed-effect models, intention-to-treat principles.[39] The models included treatment groups, time (baseline, 3 month, and 6 month), and covariates (age, sex, and BMI), as well as the group × time interactions, as fixed variables, and within-participant variation in outcome values as random variable. The random intercept for participants accounted for the dependence of repeated measures. A likelihood ratio test was also conducted to test random effect variance, ie, testing mixed model (fixed & random effect model) vs simple regression model (fixed effect only). The primary conclusions about changes in diet quality were based on between-group comparisons of AHEI-2010 scores and daily food servings at 3 and 6 months, estimated with the appropriate contrasts from the longitudinal model. To examine correlation between percentage weight and diet quality changes, Spearman correlation test was conducted between percentage weight changes and changes in overall AHEI-2010 scores of the entire cohort, at 3 and 6 months. Statistical significance was set at a two-tailed $P < 0.05$, and models were tested for goodness of fit.

RESULTS

The Consolidated Standards of Reporting Trials flow diagram of recruitment, intervention, follow-up, and analysis is shown in Figure 1. Of the 284 consecutively referred subjects screened, 136 were excluded, with reasons as stated in

Figure 1. A total of 148 participants completed all the baseline assessments and were randomized to either the control (n = 76) or intervention (n = 72) group. A total of eight enrolled participants (control group, n = 3; intervention group, n = 5) withdrew from the study. Baseline characteristics of each group are presented in Table 1. Normality tests showed that the dataset was normally distributed, except for percentage weight loss at 3 and 6 months.

Diet Quality

Two sets of food diaries could not be analyzed for AHEI-2010 score at baseline because of incomplete information. The baseline AHEI-2010 score of the entire cohort was 57.5 ± 11.4 and ranged from 31.5 to 89.9. Mean AHEI-2010 scores, food groups servings/day and sodium intake mg/day at baseline, 3, and 6 months are presented in Table 2. Using a mixed-effect model adjusted for age, sex, and BMI, there was a significant improvement in overall diet quality by 6.2 points (95% confidence interval [CI]: 3.8−8.7), $P < 0.001$) in the intervention group as compared with the control (Table 3). There were significant changes in AHEI-2010 score at 3 months by 2.5 points ($P = 0.029$) and at 6 months by 3.1 points ($P = 0.007$) compared with baseline values, showing that the AHEI-2010 score changed significantly over time. In addition, the interaction between treatment groups-by-time was significant ($P = 0.003$), indicating a significant effect of time at each group level. At participant level, there was random variability in AHEI-2010 score within participants (within participant variance = 23.49 points and SD = 4.85). The likelihood ratio test showed a significant random effect variance (test statistics = 15.46; $P < 0.001$), confirming some within-participants variability and suggesting a mixed model is a better fit for these data.

Furthermore, the analysis of individual components within the AHEI-2010 and food groups revealed which dietary components were significantly improved. The participants in the intervention group had a significantly greater reduction in intake of SSB by 0.5 servings/day (95% CI: −0.8, −0.2, $P < 0.001$) and sodium by 726 mg/day (95% CI: −983, −468, $P < 0.001$), compared with those receiving standard care. At 3 and 6 months, a significant decrease in SSB (0.8 servings/day; 0.7 servings/day, respectively) and sodium (297 mg/day; 296 mg/day, respectively) values were reported compared with baseline values. Furthermore, there were significant interactions ($P < 0.001$) in the statistical model between “dietary components and time” in each treatment group, indicating that dietary components changed significantly over time in each treatment group.

Correlation of Changes in AHEI-2010 Scores and Percentage Weight Loss

There was a significant, small positive correlation between AHEI-2010 scores and percentage weight loss at 3 ($r = 0.2$, $P = 0.048$) and 6 months ($r = 0.2$, $P = 0.004$), that is, the higher the AHEI-2010 increment, the higher the percentage weight loss (data not shown).

Mobile App Utilization

Overall, the median (interquartile range) app utilization for the intervention group was 97% (85%−100%) during the first 3 months and 92% (51%−100%) during 4 to 6 months. Based on the records in the app’s chat log, the average 2-way interactions between the participants and dietitians were 3 days per week in the first 3 months and 2 days per week in the subsequent 4 to 6 months (data not shown).

DISCUSSION

This was one of the first mHealth app intervention studies that demonstrated that overall diet quality can be improved with a remotely delivered behavioral intervention for adults with prediabetes. The analysis of components within the AHEI-2010, food group servings, and sodium intake revealed that consumption of SSB and sodium were significantly reduced. The results of this study also suggest a small positive correlation between changes in diet quality and changes in percentage weight loss in this cohort of adults with prediabetes.

The baseline AHEI-2010 score of 57.5 in the current study is similar to the score of 54.2 found amongst adults with T2DM in another local study, suggesting a pattern of low diet quality amongst adults with abnormal glucose metabolism.[17] The improvement in diet quality of 11% in the current intervention group is similar to that of another study by Brauer and colleagues (where scores were ascertained by the Canadian Healthy Eating Index and Mediterranean Diet score), following a 12-month face-to-face lifestyle intervention that aimed to alleviate metabolic syndrome.[40] A similar pattern also can be observed in a web-based app study among healthy adults, where the intervention group improved diet quality score by 6%.[14] Diet quality seems to be improved to a similar or greater degree via mHealth apps as compared with traditional face-to-face counseling.[41]

Participants in the intervention group achieved a greater increase in AHEI-2010 SSB scores and reported lower consumption of SSB compared with the control group. This is important in the context of prediabetes because the Nurses’ Health Studies have demonstrated a strong association between the consumption of sugary beverages and higher risk of T2DM.[42] Other than individualized support from dietitians to reduce SSB, this also corresponds to the app feature of automatic prompts that discourage SSB consumption by instantly prompting its users whenever they exceed their preset energy and carbohydrates recommendations for each meal. For example, automatic prompts were sent to provide sugar-free alternatives to app users when SSBs are selected in the food/beverage log-in feature. The positive outcomes in SSB intake may be attributed to the total carbohydrate monitoring feature of the app, along with the tagging of sugary drinks as “red thumb down,” which can help increase the self-awareness of users. During the intervention, one of the most common strategies used was to encourage participants in the D’LITE study to switch from their usual SSB to sugar-free alternatives. This concurs with our previous nutrient-based analysis that total sugar intakes were reduced significantly more in intervention compared with the control group.[26] Furthermore, this finding corresponds with two other studies. First, in a lifestyle intervention RCT by Partridge and colleagues,[43] a 12-week mHealth program was found to have significantly greater improvement in sugary soft drink consumption in participants in the intervention group compared with those in the control group.[43] Second, in an intervention study by Brauer and colleagues[40] among adults with diabetes risk factors, which included traditional face-to-face consultation, voluntary group sessions, between-visit phone calls, and letters, sugar intake (g/day) and SSB intake were lower at 3 and 12 months.[40]

The positive outcomes observed in sodium subcomponent post-intervention corroborate findings from a recent study using remote dietary counseling in a group of patients with renal disease[44] and the aforementioned study by Brauer and colleague.[40] The nBuddy Diabetes app automatically generates a list of healthier alternatives to foods logged in by users. Therefore, the support from research dietitians through the app, and instantaneous feedback of suggestions for lower-energy or carbohydrates alternatives, could have also deterred users from consuming sodium-laden foods such as processed meat or salted egg and fish, which are popular local delicacies. Reduced sodium intake was previously reported to be accompanied by lower energy intake and, concomitantly, lower carbohydrate intake.[45]

The current study extends the evidence presented by Brauer and colleagues[40] in a single-arm intervention study that found within-group differences post-intervention at 3 months in individual food-based components such as whole fruits and whole grains. Although there were improvements within groups, the current study suggests that there may be minimal individual component differences (non-inferior) between the intervention by the mHealth app compared with usual care. This may further suggest that dietary intervention would need to be specific and targeted at improving each food group, beyond the focus on energy, carbohydrates, sugar, and sodium.

Dietary interventions remain one of the cornerstones in diabetes prevention, and research centered around nutrients, such as macronutrient amount and distribution, and clinical outcomes such as weight loss is important.[46] However, because diet quality alone has consistently been inversely associated with the risk of developing T2DM, research on ways to improve food-based recommendations, beyond the primary focus on nutrients and its impact on weight, also would be very helpful in this growing population.[47,48] Fung and colleagues[48] previously demonstrated that increment in diet quality scores ascertained by various diet quality indices (including AHEI-2010) is associated with reduced long-term weight gain.[49] Although diet quality was not a significant predictor of weight loss, it influenced weight change (higher HEI-2005 score associated with increased weight loss) in an RCT examining diet quality and weight changes in a cohort of overweight and obese women postpartum.[50] Specifically in those at risk of T2DM, an increase in AHEI-2010 score was associated with significant weight loss after an intensive face-to-face lifestyle intervention with the diabetes prevention program, ie, per 10-point increase associated with 1.2-kg weight loss.[51] The positive correlation found in the current study adds to this knowledge by suggesting that this correlation between diet quality and weight changes exists even for interventions that are delivered on an mHealth platform.

Strengths and Limitations

This study has several strengths. Participants' app engagement (meal and weight logging) and weight were objectively measured. Apart from the initial visit, and 3- and 6-month visits solely for outcome measurements, all other aspects of the study were delivered remotely, thus using fewer resources and allowing the intervention to be scalable to a larger population. The intervention still can be delivered in situations where physical visits are not an option, because of its remote nature.[52] The use of an established diet quality index (AHEI-2010), with an inverse correlation to diabetes risk, indirectly measures the far-reaching effects of the diet in delaying the development of T2DM.[53] The statistical analyses also accounted for repeated measures over time. However, the study is not without limitations. The sample size calculation performed for this trial used weight loss, and not diet quality/AHEI-2010, as its primary outcome. As with all studies with self-reported dietary data, there could be over-reporting of socially acceptable "healthy food/drinks" and underreporting of "unhealthy food/drinks." However, participants were encouraged to be honest with the reporting while doing the food diaries, and nutrient analyses were reviewed by research staff not involved in the delivery of the mHealth behavioral intervention. Finally, participants in this study may not represent marginalized populations that are not literate in English or those without access to a smart phone. Therefore, results from the current study also would not be generalizable to individuals in Singapore who are not literate in English and do not have access to a smart phone.

CONCLUSIONS

A behavioral intervention mHealth-app program supported by dietitians has the potential to improve diet quality in adults with prediabetes in Singapore. Results also suggest a small positive correlation between changes in AHEI-2010 scores from baseline and percentage weight loss at 3 and 6 months.

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STATEMENT OF POTENTIAL CONFLICT OF INTEREST

No potential conflict of interest was reported by the authors.

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AUTHOR CONTRIBUTIONS

S. L. L. is the Principal Investigator for this study. C. H. and S. L. L. conceived the presented idea and developed the study design, with A. G. leading the statistical analysis plan. All authors carried out the project or analyzed the data. C. H. and J. J. drafted the article, and all authors provided critical revisions and final approval of the manuscript. All authors had access to the data in the study and take responsibility for the integrity of the reported findings. All authors fulfil the ICMJE criteria for authorship.