Received: 19 May 2023 | Revised: 18 March 2024 | Accepted: 26 March 2024

DOI: 10.1111/nbu.12673

EMERGING RESEARCH

Nutrition Bulletin

The development of an EU-wide nutrition and physical activity expert knowledge base to support a personalised mobile application across various EU population groups

S. L. Wilson-Barnes[1] | I. Pagkalos[2] | E. Patra[2] | A. Kokkinopoulou[2] | M. Hassapidou[2] | E. Lalama[3] | M. Csanalosi[3] | S. Kabisch[3] | A. F. H. Pfeiffer[3] | E. DeCorte[4] | V. Cornelissen[4] | P. Bacelar[5] | S. Balula Dias[6] | K. Stefanidis[7] | D. Tsatsou[7] | L. Gymnopoulos[7] | K. Dimitropoulos[7] | K. Rouskas[7] | N. Argiriou[7] | R. Leoni[8] | J. M. Botana[9] | D. Russell[10] | S. A. Lanham-New[1] | K. Hart[1]

[1]School of Biosciences & Medicine, University of Surrey, Guildford, UK

[2]Department of Nutritional Sciences and Dietetics, International Hellenic University, Thessaloniki, Greece

[3]Department of Endocrinology, Diabetes and Nutrition, Charité Universitätsmedizin Berlin, Berlin, Germany

[4]Department of Rehabilitation Sciences and Department of Cardiovascular Sciences, Katholieke Universiteit Leuven, Leuven, Belgium

[5]Healthium/Nutrium Software, Porto e Região, Portugal

[6]Interdisciplinary Centre for the Study of Human Performance (CIPER), Faculdade de Motricidade Human, Universidade de Lisboa, Lisbon, Portugal

[7]Centre for Research & Technology Hellas, Thessaloniki, Greece

[8]Datawizard, Rome, Italy

[9]GrupoCMC, Madrid, Spain

[10]Ocado Group, Hatfield, UK

Correspondence
S. L. Wilson-Barnes, Department of Nutritional Sciences, Faculty of Health and Medical Sciences, University of Surrey, Guildford, Surrey GU2 7XH, UK.
Email: saskiaw940@hotmail.com

Funding information
HORIZON EUROPE European Innovation Council, Grant/Award Number: 817732

Abstract

A healthy lifestyle comprising regular physical activity and an adequate diet is imperative for the prevention of non-communicable diseases such as hypertension and some cancers. Advances in information computer technology offer the opportunity to provide personalised lifestyle advice directly to the individual through devices such as smartphones or tablets. The overall aim of the *PROTEIN* project (Wilson-Barnes et al., 2021) was to develop a smartphone application that could provide tailored and dynamic nutrition and physical activity advice directly to the individual in real time. However, to create this mobile health (m-health) smartphone application, a knowledge base of reference ranges for macro-/micronutrient intake, anthropometry, biochemical, physiological and sleep parameters was required to underpin the parameters of the recommender systems. Therefore, the principal aim of this emerging research paper is to describe the process by which experts in nutrition and physiology from the *PROTEIN* consortium collaborated to develop the nutritional and physical activity requirements, based upon existing recommendations, for 10 separate population groups living within the EU including, but not limited to healthy adults, adults with type 2 diabetes mellitus, cardiovascular disease, excess weight, obesity and iron deficiency anaemia. A secondary aim is to describe the development of a library of 24-h meal plans appropriate for the same groups and also encompassing various dietary preferences and allergies. Overall, the consortium devised an extensive nutrition and physical activity knowledge base that is pertinent to 10 separate EU user groups, is available in 7 different languages and is practically implemented via a library of culturally appropriate, 24-h meal plans.

KEYWORDS
dietary advice, m-health, personalised nutrition, public health

INTRODUCTION

There is a broad consensus as to what constitutes a 'healthy' lifestyle and diet for the general population, such as the visual models created by Public Health England within the United Kingdom (the 'Eatwell Guide', (Public Health England, 2018)) and the Food Pyramid, now updated to the 'Choose My Plate' model, within the United States (United States Department of Agriculture (USDA), 2019). However, while these generic models have undoubtedly been refined in recent years, there has been a parallel shift towards greater tailoring of advice to the individual, considering their lifestyle, dietary preferences, physiology, genetics and even social demographics. This is commonly referred to as 'Personalised Nutrition' or 'Precision Nutrition' and with further evidence emerging from genetic studies (Mullins et al., 2020); there is a clear need for modern nutritional science to take a more personalised approach to providing dietary and lifestyle advice.

The popularity of online tools to access healthcare professionals and advice has surged following the coronavirus pandemic and with smartphone ownership across the EU estimated at 82% in 2022 (Smartphone Market in Europe, 2023), this suggests that virtual healthcare is widely sought after. In line with this, there are already a vast number of diet and health mobile applications ('apps') available on the market, although few provide quality scientific and expert-driven advice to their end users. In fact, some of the most popular dietary assessment apps, providing extensive databases of commercial food products, are reliant on crowdsourcing for their nutritional information, with little to no validation of the dietary data quality. Furthermore, often the most user-friendly apps, and therefore those receiving the highest customer ratings and downloads, are technologically rather than scientifically driven (König et al., 2021). Therefore, the safety of any nutritional and health messages communicated through these apps remains unclear and often unvalidated by experts in the field. Although scientifically robust online personalisation systems do exist, such as the system developed by the EU-funded *Food4Me* project (Celis-Morales et al., 2015, 2017) and the *PREVENTOMICS* study (Aldubayan et al., 2022), the challenge now is to apply these systems in a fully automated methodology across a variety of real-time and real-user scenarios from various population groups. This will create a more dynamic system, which responds to specific user behaviours and is therefore anticipated to promote greater engagement and ultimately, greater health benefits for the end user (Wilson-Barnes et al., 2021).

Therefore, the overall aim of the *PROTEIN* project (Wilson-Barnes et al., 2021) was to combine novel information computer technology (such as the use of artificial intelligence [AI] and sensor technology), big-data management capabilities and an evidence-based repository, generated by experts in the field of nutrition, biochemistry, medicine and physical activity, to provide the end-user with app-delivered personalised, dynamic nutrition and lifestyle goals (or targets) to achieve a healthier lifestyle, relative to their requirements and cognisant of their actual daily behaviours (shown in Figure 1). This system is being trialled in a variety of user groups across the EU to involve a varied population including sub-groups such as healthy older adults, individuals with type 2 diabetes mellitus (T2DM), cardiovascular disease and athletes (see Table 1). The user groups were divided to ensure that they were under medical and nutritionist supervision due to their presenting medical condition and to ensure the safety of the application recommendations. The principal aim of this methodology paper is to present the development of the evidence-based, expert-approved conceptual 'rules' that underpin the mobile application, specifically the database of user group-specific nutrition knowledge and physical activity guidelines. A parallel objective of this work was to produce a repository of nutritionally balanced meals and recipes to support the dietary guidance provided by the reasoning-based decision support system within the AI advisor.

DIETARY PARAMETERS FOR THE PROTEIN APP

Within the *PROTEIN* project, the consortium collaborated to provide a common set of guidelines specific to the user groups identified (see Table 1) across five different EU countries (United Kingdom, Greece, Belgium, Germany and Portugal). For users with clinical requirements, such as patients with cardiovascular disease, evidence from professional bodies and overall EU-wide guidance was collated to be incorporated as the nutrition guidelines within the *PROTEIN* mobile app knowledge base. The methodology followed by the consortium, from initial discussions between consortium experts to the final integration and translation into multiple EU languages for mobile app usage, is illustrated in Figure 2.

While the *PROTEIN* app was intended to be applicable across the EU, localisation to the countries directly involved in the project was only exclusively achieved via translation of the agreed recommendations into seven further languages including Spanish, French, German, Italian, Greek, Portuguese and Dutch by native speakers. Overall, for recommendations on macronutrient intakes, the experts utilised the most up-to-date evidence published by the European Food Safety Authority (EFSA) (EFSA, 2012, 2010, 2017) and applied these to each subgroup within the project, as shown in Table 2. The list of micronutrients and food recommendations that were highlighted for each user group (UG) were as follows: iron, calcium, vitamin D, vitamin C, fibre and fruit/vegetable intake. Iron was identified as an important micronutrient to

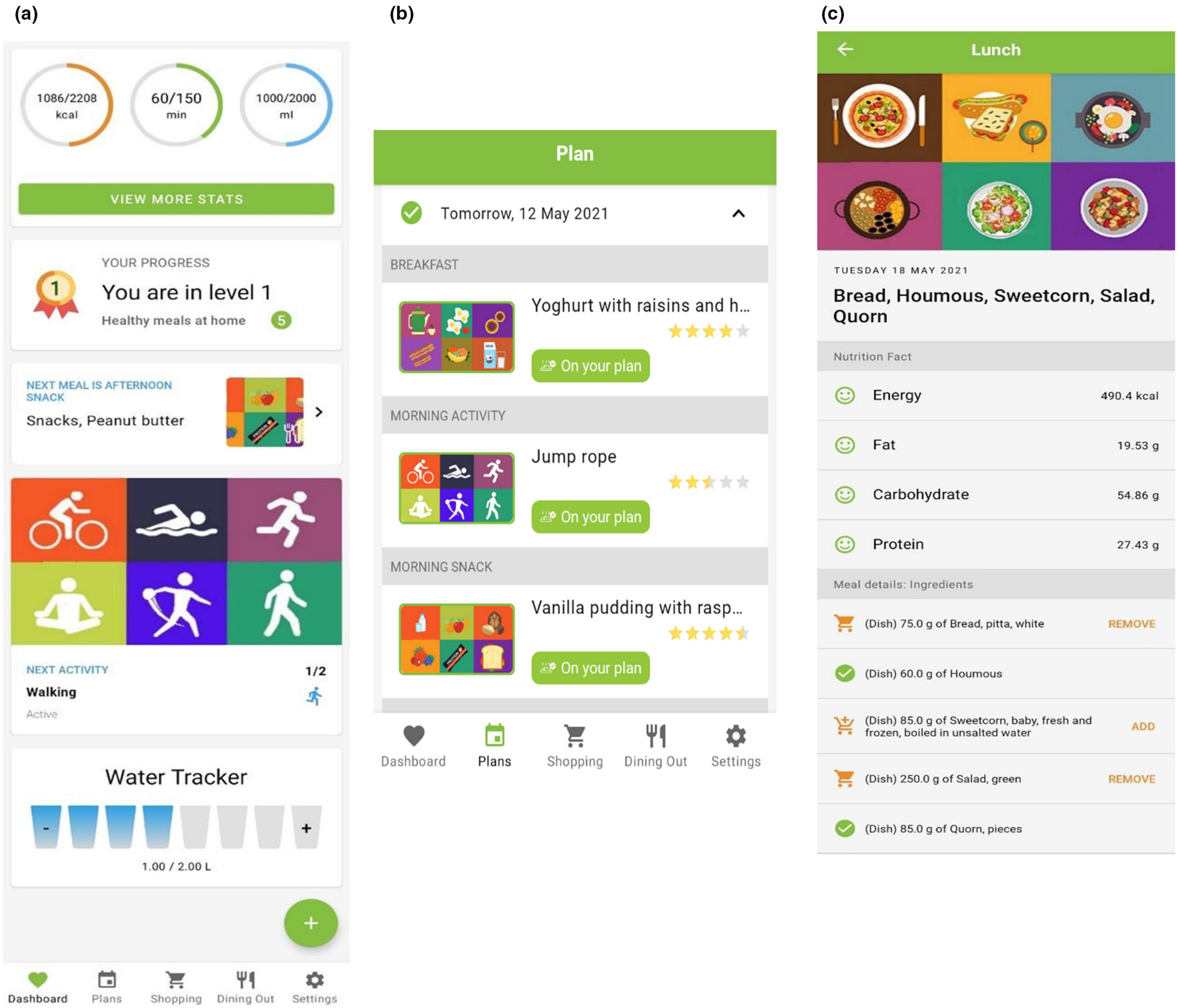

FIGURE 1 Screenshot of the PROTEIN mobile application demonstrating the (a) main dashboard, (b) nutrition and physical activity plans (NAP) and (c) meal summary.

be monitored and to provide specific recommendations due to the inclusion of a clinical iron deficiency (such as anaemia) sub-group. Vitamin D and calcium were also included as key components of the diet due to their direct influence on musculoskeletal health and the high prevalence of vitamin D deficiency within Europe (Cashman et al., 2016); recommendations for these were set at 10 µg/day and 950–1150 mg/day, respectively (as shown in Table 3). The experts agreed that, despite the EU regulations suggesting a higher intake of 15 µg/d for vitamin D, this recommendation is rarely achievable through dietary intake alone and, were this to be implemented as a hard rule within the mobile application, potentially unachievable intakes of unfamiliar foods would be required for many users. Moreover, users who are vitamin D deficient would require medical support and supplementation to increase their levels, which was beyond the initial scope of the application, which primarily focussed on dietary optimisation. Therefore, a more conservative intake of 10 µg/day was set to maintain serum-25-hydroxyvitamin D levels above deficiency (25[OH]D >25 nmol/L) for most of the population as per the current UK guidelines (SACN, 2019).

The EFSA report identifies that diets high in dietary fibre intake are associated with a healthy balanced diet and weight maintenance (EFSA, 2010). Furthermore, dietary fibre is important for overall health (Barber et al., 2020; Veronese et al., 2018), in the management of cardiovascular disease and hypertension (Reynolds et al., 2022,) and in reducing the risk of certain cancers (Oh et al., 2019). Therefore, a dietary fibre intake of 25 g for female and 30 g for male participants was selected by the consortium for overall health and gut motility. This was of particular importance for participants within the poor-quality diet sub-group, which was defined by the consortium as a low fruit and vegetable intake (<3 portions/day). The associations found between fibre intake and weight maintenance are also applicable for the UGs under medical or nutritionist supervision (EFSA, 2010) since dietary fibre has also been shown to reduce the risk of T2DM (Weickert & Pfeiffer, 2018). Therefore, it was considered imperative to include daily fibre targets within the system knowledge base since it applied to at least five of the population sub-groups. Furthermore, the experts agreed that it would be of interest to monitor fruit and vegetable intake (portions/day), to reflect the likely lower intake within the adults with poor-quality diets sub-group. Portion sizes for fruit and vegetables were determined as 80 g/portion for adults. Experts agreed that five portions of fruit/vegetables were to be suggested daily by the recommender system, thus, amounting to a total of 400 g/day of fruit and vegetables, which is in line with the Food and Agriculture Organization of the United Nations and WHO recommendations (FAO, 2020). The additional micronutrient recommendations agreed by the consortium for each subgroup are presented below in further detail (Table 2).

PHYSIOLOGICAL & BIOCHEMICAL VARIABLES

It was imperative as part of the *PROTEIN* project to also develop physiological reference ranges for all UGs to provide 'targets' or physiological 'goals' for parameters such as weight or blood pressure (BP) (WHO, 2011) and the steps taken to generate the database of biochemical

TABLE 1 Detailed description of the user and sub-groups recruited for the PROTEIN project.

User group		
A	**B**	**C**
General public	**Under nutritionist supervision**	**Under medical/nutritionist supervision**
	Sub-groups	
Healthy Adults	Adults who are overweight (>25 kg/m^2)	Adults with obesity (>30 kg/m^2)
Healthy Adolescents (14–18 years)	Athletes	Patients with type 2 diabetes
Healthy Older Adults (65+ years)		Patients with cardiovascular disease
		Adults who consume a poor-quality diet (<3 portions of fruit/veg per day)
		Adults with iron deficiency anaemia (<120 g/L)

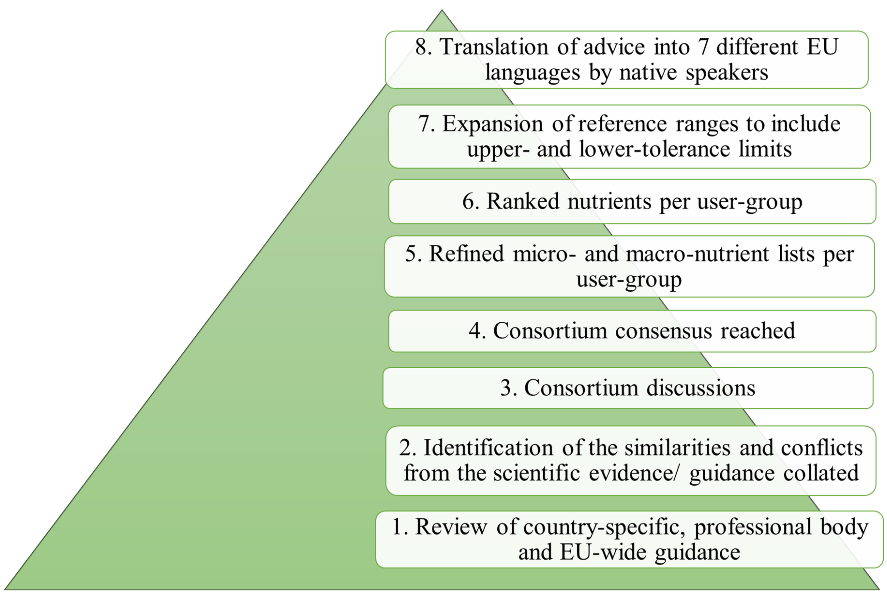

FIGURE 2 Processes followed by the consortium to reach a consensus on a common set of dietary recommendations for end-users of the PROTEIN mobile application and to incorporate these into the application.

TABLE 2 Dietary reference values set for the population groups included in the PROTEIN study.

		Macronutrients								Micronutrients				Other		
	Gender	Energy (kcal/day)	CHO (% EI)	Sugar (% EI)	Protein (g/kg/BW)	Fat (% EI)	Sat Fat (% EI)	N3 FA (mg/day)	Salt (g/day)	Iron (mg/day)	Calcium (mg/day)	Vit D (μg/day)	Vit C (mg/day)	Fibre (g/day)	Fruit (Portion)	Vegetables (Portion)
A																
Adults	Male	2500	50	<10	0.66	<30	<10	160	<5	11	950	10	95	30	2	3
	Female	2000	50	<10	0.66	<30	<10	90	<5	16	950	10	80	25	2	3
Adolescents	Male	2900	45–60	<10	0.70	<30	<10	125	<5	11	1150	10	90	20	2	3
	Female	2300	45–60	<10	0.68	<30	<10	85	<5	13	1150	10	100	20	2	3
Older Adults	Male	2300	50	<10	0.66	<30	<10	160	<5	9	950	10	95	30	2	3
	Female	1800	50	<10	0.66	<30	<10	90	<5	9	950	10	80	25	2	3
B																
OW	Male	2500	50	<10	0.66	<30	<10	160	<5	11	950	10	95	30	2	3
	Female	2000	50	<10	0.66	<30	<10	90	<5	16	950	10	80	25	2	3
Athletes	Male	40–70[a]	6–10[b]	<10	–	<30	<10	160	<5	11	950	10	95	30	2	3
	Female	40–70[a]	6–10[b]	<10	–	<30	<10	90	<5	16	950	10	80	25	2	3
C																
OB	Male	2500	50	<10	0.66	<30	<10	160	<5	11	950	10	95	30	2	3
	Female	2000	50	<10	0.66	<30	<10	90	<5	16	950	10	80	25	2	3
CVD	Male	2500	50	<10	0.66	<30	<10	160	<5	11	950	10	95	30–45	2	3
	Female	2000	50	<10	0.66	<30	<10	90	<5	15	950	10	80	30–45	2	3
T2DM	Male	2200–2400	50	<10	0.80	<30	<10	160	<5	11	1000	10	110	30–45	2	3
	Female	1700–1900	50	<10	0.80	<30	<10	90	<5	16	1000	10	95	30–45	2	3
IDA	Male	2500	50	<10	0.66	<30	<10	160	<5	11	950	10	95	30	2	3
	Female	2000	50	<10	0.66	<30	<10	90	<5	16	950	10	80	25	2	3
PQD	Male	2500	50	<10	0.66	<30	<10	160	<5	11	950	10	95	30–35	2	3
	Female	2000	50	<10	0.66	<30	<10	90	<5	16	950	10	80	30–35	2	3

Abbreviations: BW, bodyweight; CHO, carbohydrate; CVD, adults with cardiovascular disease; IDA, adults with iron deficiency anaemia; N3 FA, omega 3 fatty acids; OW, adults that are overweight; OB, adults that are obese; PQD, adults with poor-quality diets; Sat Fat, saturated fat; T2DM, adults with type 2 diabetes mellitus.

[a]kcal/kg BW/day.

[b]g/kg BW/day.

TABLE 3 Physiological and biochemical reference values set for the population groups included in the PROTEIN study.

		Physiology					Biochemistry		
	Gender	BMI (kg/m²)	Waist (cm)	Waist:Hip ratio	Sleep (hours)	Blood glucose (mmol/L)	LDL-C (mmol/L)	HDL-C (mmol/L)	TAG (mmol/L)
A									
Adults	Male	18.5–24.99	<102	<1.0	7–9	≤5.6	≤3.0	≥1.0	≤1.7
	Female	18.5–24.99	<88	<0.85	7–9	≤5.6	≤3.0	≥1.2	≤1.7
Adolescents	Male	–	–	–	8–10	–	–	–	–
	Female	–	–	–	8–10	–	–	–	–
Older Adults	Male	18.5–24.99	<102	<1.0	7–8	≤5.6	≤3.0	≥1.0	≤1.7
	Female	18.5–24.99	<88	<0.85	7–8	≤5.6	≤3.0	≥1.2	≤1.7
B									
OW	Male	18.5–24.99	<102	<1.0	7–9	≤5.6	≤3.0	≥1.0	≤1.7
	Female	18.5–24.99	<88	<0.85	7–9	≤5.6	≤3.0	≥1.2	≤1.7
Athletes	Male	N/A[a]	–	–	7–9	≤5.6	≤3.0	≥1.0	≤1.7
	Female	N/A[a]	–	–	7–9	≤5.6	≤3.0	≥1.2	≤1.7
C									
OB	Male	18.5–24.99	<102	<1.0	7–9	≤5.6	≤3.0	≥1.0	≤1.7
	Female	18.5–24.99	<88	<0.85	7–9	≤5.6	≤3.0	≥1.2	≤1.7
CVD	Male	18.5–24.99	<102	<1.0	7–9	≤5.6	≤2.6	≥1.0	≤1.7
	Female	18.5–24.99	<88	<0.85	7–9	≤5.6	≤2.6	≥1.2	≤1.7
T2DM	Male	18.5–24.99	<102	<1.0	7–9	≤5.6	High risk ≤3[b]	≥1.03[b]	≤1.7
	Female	18.5–24.99	<88	<0.85	7–9	≤5.6	Very high risk ≤2.6[b]	≥1.29[b]	≤1.7
IDA	Male	18.5–24.99	<102	<1.0	7–9	≤5.6	≤3.0	≥1.0	≤1.7
	Female	18.5–24.99	<88	<0.85	7–9	≤5.6	≤3.0	≥1.2	≤1.7
PQD	Male	18.5–24.99	<102	<1.0	7–9	≤5.6	≤3.0	≥1.0	≤1.7
	Female	18.5–24.99	<88	<0.85	7–9	≤5.6	≤3.0	≥1.2	≤1.7

Abbreviations: BMI, Body mass index; CVD, adults with cardiovascular disease; HDL-C, high-density lipoprotein cholesterol; IDA, adults with iron deficiency anaemia; LDL-C, low-density lipoproteins cholesterol; OW, adults who are overweight; OB, adults with obesity; PQD, adults with poor-quality diets; T2DM, adults with type 2 diabetes mellitus; TAG, triacylglycerol.

[a]BMI is not applicable for the athlete (Kasper et al., 2021) and adolescent (Vanderwall et al., 2017) groups.

[b]This was applied to males and females with diabetes if they were considered to be at high or very high risk of a cardiovascular event within the next 10 years in line with the ESC guidelines on diabetes (Rydén et al., 2013).

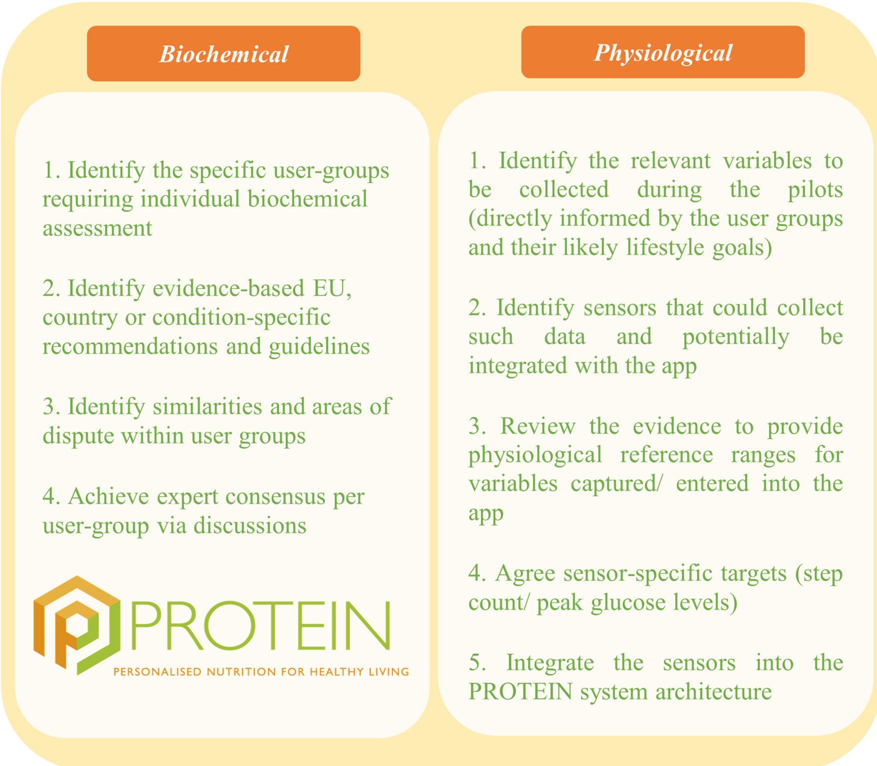

FIGURE 3 Processes followed by the consortium to reach a consensus on biochemical and physiological reference ranges for end-users of the PROTEIN mobile application.

and physiological variables and their associated reference ranges are described in Figure 3 (Bilionis et al., 2021; Konstantinidis et al., 2020; Theodoridis et al., 2020; Wilson-Barnes et al., 2021). The relevant variables identified by the experts included anthropometrics (specifically body mass index [BMI], waist circumference and waist–hip ratio), blood biochemical parameters (lipid levels), heart rate (HR) and sleep quality. The anthropometric measures were chosen due to their familiarity among health professionals, relative ease of measurement, lack of specialist equipment required and use as markers of excess weight and/or morbidity (Pintér et al., 2017). The cut-offs for waist and hip measurements agreed as applicable to the *PROTEIN* UGs are shown in Table 3 and derived from those of the International Society for the Advancement of Kinanthropometry (ISAK) (ISAK, 2022). It is important to acknowledge that specific cut-offs for BMI and waist circumference were not provided dependent on ethnicity for all user groups, which is a limitation of this version of the *PROTEIN* app. However, it is key to highlight that adults within groups B and C were under specialist medical/nutritionist supervision as shown in Table 1. Furthermore, the athlete group did not have a waist-to-hip ratio defined as this is largely dependent on their sport modality, body composition, ethnicity, gender and age. Moreover, BMI is not a useful indicator for the athlete and adolescent groups compared to body fat percentage (Kasper et al., 2021; Vanderwall et al., 2017).

Reference ranges for fasting blood glucose reference ranges were taken from the WHO recommendations (Diabetes, 2022) and the European Society of Cardiology (Cosentino et al., 2020). These levels represent recognised criteria for the primary prevention of T2DM, whereby fasting blood glucose levels above 5.6 mmol/L could potentially progress to impaired glucose tolerance and diabetes mellitus (Cosentino et al., 2020; Diabetes, 2022). Adults with T2DM were the only sub-group to be provided with direct feedback on their glucose levels during the project, as a continuous glucose monitor (Freestyle Libre 1 & 3, Abbott) was successfully integrated within the *PROTEIN* mobile suite. Participants on insulin or taking medication to increase insulin excretion are not included within the scope of the app. The sensor provided feedback on time in range (TIR), which is associated with haemoglobin A1C (HbA1c) levels (Battelino et al., 2019), and deviations from the TIR target trigger the AI advisor to recommend a 10% increase/decrease in dietary carbohydrate intake in line with evidence from previous literature (Evert et al., 2014). The TIR reference ranges used for the sensor refer to the time spent in an individual's target glucose range; from 70 to 180 mg/dL (3.9–10 mmol/L) (Danne et al., 2017). A high glucose level was defined as >140 mg/dL over a time range of 2–4 h after a meal. A 10% increase/decrease in the carbohydrate recommendations provided by the AI advisor only occurred if the participant's TIR deviated above the threshold of <70 mg/dL and >140 mg/dL over a time range of 2–4 h on two or more separate occasions following the consumption of one specific meal. Foods, apart from vegetables and pulses, that cause high glucose levels would also activate a push notification directly to the user.

Nutrition Bulletin

Non-sensor-related biochemical parameters that were agreed for inclusion within the *PROTEIN* application suite were lipid levels (including high-density/low-density lipoproteins; HDL-C and LDL-C and triacylglycerides; TAG) as these represent key variables for the health hazard prediction within the mobile suite, specifically for adults under medical or nutritionist supervision (UG C). Elevated levels of plasma LDL-C have a causal role in atherosclerosis. Moreover, the reduction in LDL-C decreases cardiovascular (CV) events, whereas low HDL-C is associated with increased CV risk (Piepoli et al., 2016). To improve blood cholesterol levels, lifestyle and dietary changes are recommended for all people with CV risk factors, such as older age, excess weight or increased blood pressure (>140/90 mmHg) (Piepoli et al., 2016), warranting the inclusion of these variables in the *PROTEIN* system. Reference ranges for the blood lipid levels were collated and defined for each user group using the European guidelines on cardiovascular disease prevention in clinical practice (Piepoli et al., 2016), as presented in Table 3. However, there was no sensor integrated within the *PROTEIN* app for lipid values, and medical professionals supervising users are expected to input the lipid values of the user into the app when setting up their user profile. Furthermore, the system does not track these values or give target goals for LDL, nor does it base its meal recommendations on these values. Resting heart rate is another good predictor of physical health and can identify the intensity of physical activities the user may be involved in (from high, moderate to low intensity). Overall, the non-exercising heart rate was considered normal between 60 and 100 bpm (Avram et al., 2019) and this reference range was entered in the *PROTEIN* system. Resting heart rate could only be entered directly into the app by the medical professional upon user set-up.

Evidence from the literature suggests that sleep is imperative for overall health (Chaput et al., 2016, 2017; St-Onge et al., 2016) being critical for metabolism, appetite regulation and the functioning of the immune, hormonal and cardiovascular systems (Medic et al., 2017). A healthy sleeping regime comprises many aspects, including adequate duration, good quality, appropriate timing and the absence of sleep disorders such as apnoea and insomnia (Buysse, 2014). As habitual short sleep duration has been associated with adverse health outcomes, namely obesity (Wu et al., 2014), T2DM (Shan et al., 2015), hypertension (Wang et al., 2015), CVD (Wang et al., 2016), depression (Zhai et al., 2015) and all-cause mortality (Shen et al., 2016), it was considered essential to provide guidance on sleep duration within the expert knowledge base. Furthermore, sleep length was also added as guidance for the athlete group to prevent the consequences of over-training (Meeusen et al., 2013), associated with acute fatigue and decreases in performance. The consortium noted that sufficient sleep duration requirements vary across the lifespan and from person to person but agreed to utilise the guidance proposed by the American Academy of Sleep Medicine and Sleep Research Society, which is presented in Table 3, for all UGs. Medical professionals directly involved in the care of users were able to add the average sleep duration of their users during set-up.

The authors acknowledge that genetics and the gut microbiome may be key components of personalised nutrition. However, since at the time of the app development, there was a lack of evidence on how an individual's genetic or microbiome profile should determine dietary advice, at a whole diet level, the *PROTEIN* consortium did not include these aspects within the knowledge base. In addition, the partners agreed that combining genetic-related advice with biochemical, physiological and dietary preference variables would further limit the choices that would be available to the end user of the *PROTEIN* app. Although it is not yet integrated within the *PROTEIN* platform, experts in genetics conducted a sub-study investigating the genetic and microbiome profiles of adults with CVD, T2DM, obesity and healthy controls across the EU, alongside their use of the *PROTEIN* mobile app to assess the feasibility of personalising according to these variables. These datasets will hopefully be released in the near future by *PROTEIN* consortium partners.

REFERENCE RANGES FOR PHYSICAL ACTIVITY

According to the WHO (World Health Organization, 2022a), regular physical activity (PA) is a well-established protective factor for the prevention and treatment of the leading non-communicable diseases (NCDs) such as cardiovascular disease, some cancers and T2DM, while also impacting favourably on other NCD risk factors such as hypertension and excess weight. PA is also associated with improved mental health, a delay in the onset of dementia and an improvement in perceived quality of life and wellbeing (Stubbs et al., 2018).

Relevant partners of the *PROTEIN* consortium collaborated to establish PA recommendations which outlined the optimal frequency, duration, intensity and total energy expenditure suggested for each UG. Recommendations from the Global Recommendations on Physical Activity for Health, published by World Health Organization (2022a, 2022b), were adopted, as shown in Table 4, and were in line with the recommendations set out by the European Association of Preventive Cardiology (EAPC), which were also considered. Other aspects of physical fitness highlighted within the EAPC report such as strength/resistance training, balance and flexibility (Vanhees et al., 2012) were also considered by the consortium, according to the target UG.

For those users aiming to achieve a clinically significant weight loss, such as 10% of bodyweight, (i.e.

TABLE 4 Recommended physical activity levels for all population groups included in the PROTEIN study.

	Gender	Frequency (days/week)	Duration (Minutes)	Intensity (Light/moderate/vigorous)	Energy expenditure (kcal/week)
A					
Adults	Male	≥5	≥30[a]	Moderate	≥1000
	Female	≥5	≥30[a]	Moderate	≥1000
Adolescents	Male	≥5	≥60	Moderate-vigorous	≥1500
	Female	≥5	≥60	Moderate-vigorous	≥1500
Older Adults	Male	≥5	≥30[a]	Moderate	≥1000
	Female	≥5	≥30[a]	Moderate	≥1000
B					
OW	Male	≥5	≥30[a]	Moderate	≥1000
	Female	≥5	≥30[a]	Moderate	≥1000
Athletes	Male	N/A	N/A	N/A	N/A
	Female				
C					
OB	Male	≥5	≥30[a]	Moderate-vigorous	≥1500
	Female	≥5	≥30[a]	Moderate-vigorous	≥1500
CVD	Male	≥5	≥60	Moderate-vigorous	≥1000
	Female	≥5	≥60	Moderate-vigorous	≥1000
T2DM	Male	≥5	≥30[a]	Moderate-vigorous	≥1000
	Female	≥5	≥30[a]	Moderate-vigorous	≥1000
IDA	Male	≥5	≥30[a]	Moderate	≥1000
	Female	≥5	≥30[a]	Moderate	≥1000
PQD	Male	≥5	≥30[a]	Moderate	≥1000
	Female	≥5	≥30[a]	Moderate	≥1000

Abbreviations: CVD, adults with cardiovascular disease; IDA, adults with iron deficiency anaemia; OB, adults with obesity; OW, adults that are overweight; PQD, adults with poor-quality diets; T2DM, adults with type 2 diabetes mellitus.

[a]≥30 min/day or ≥150 min throughout the week.

the users with obesity) larger volumes of exercise are necessary to encourage an energy deficit, therefore total estimated energy expenditure (kcal/week) was increased for adults who were obese. Specifically, the American College of Sports Medicine (ACSM) (Donnelly et al., 2009) states that participation in over 150–250 min/week of moderate PA may be required to induce clinically significant weight loss. It is also noted within the same report that moderate PA recommendations should also be provided along with adequate dietary advice or restriction. Some evidence shows that in adults with obesity, resistance training may be beneficial for the preservation of lean body mass (Lopez et al., 2022), therefore this was considered in the training modalities that were recommended to participants by the mobile application.

MEAL PLANS & RECIPES

Due to the lack of availability of an established and suitable meal/recipe database which could be incorporated into the *PROTEIN* application, as originally intended, a secondary aim was established to develop a library of suitable 24-h meal plans. These were designed to be appropriate for the countries and user groups identified in the trial and which would meet the macro- and micronutrient recommendations for each group as described in Table 2, while also encompassing different dietary preferences (vegan or red-meat avoider) and allergies (gluten free or dairy free) likely to be represented within the user population. The specific allergies incorporated within the system are detailed within the nutrition ontology developed for the application (Tsatsou et al., 2021), which included, but was not limited to, gluten, lactose, crustacean/shellfish, egg, milk and soy. The dietary and cultural preferences available for users to choose from within the *PROTEIN* project were lacto-vegetarian, ovo-vegetarian, lacto-ovo-vegetarian, red-meat avoider, vegan, pescatarian, halal and kosher. Both filters were recognised by the Nutrium database (Nutrium, 2022), which ensured that all meals developed within the system were appropriate for each participant's specific allergy or preference. The meals were developed by the nutrition and dietetics professionals from five

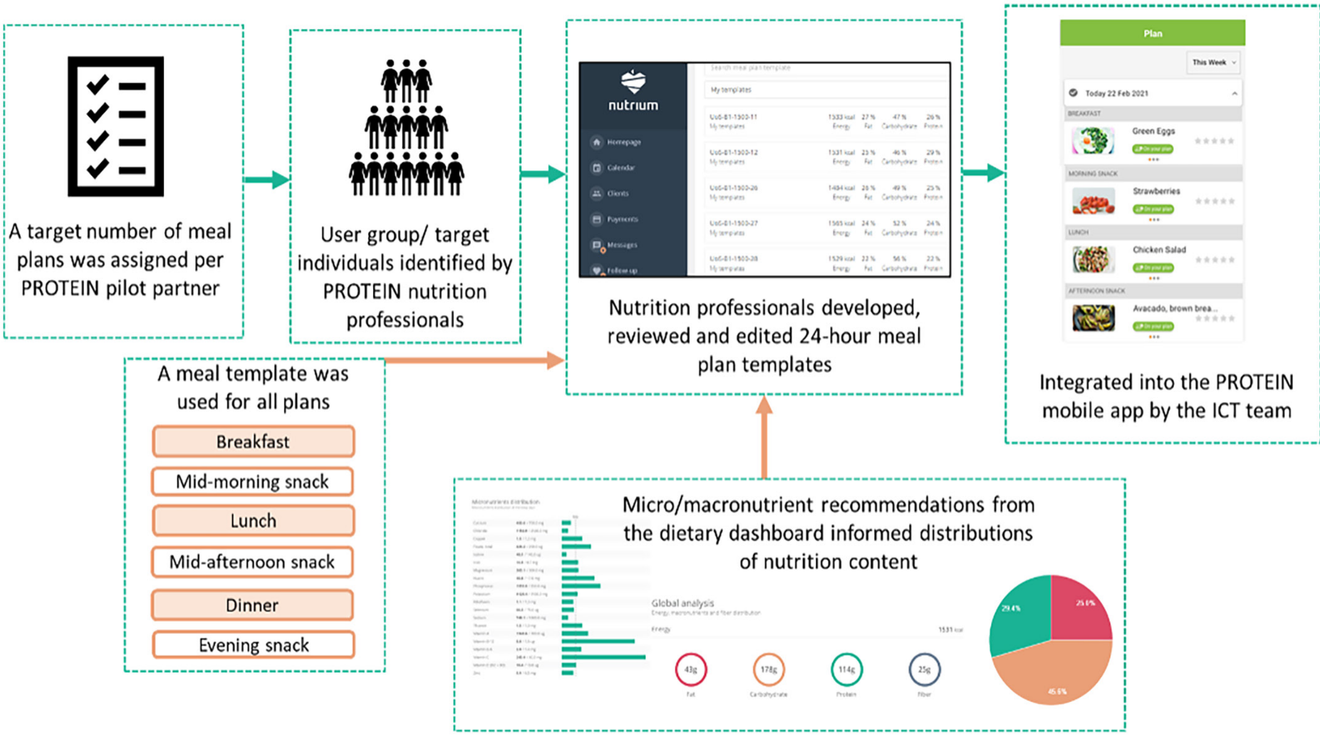

FIGURE 4 A diagram to illustrate the methods utilised by nutrition professionals within the PROTEIN consortium to develop 24 hour meal plans within Nutrium. ICT, information computer technology.

different institutions (Germany, Belgium, Portugal, Greece and United Kingdom) who utilised their local knowledge of country-specific foods, country-specific fortification practices and culturally appropriate foods to create 24-h meal plans appropriate for their respective EU country and specific user groups (as presented in Figure 4). Each meal plan comprised three separate meals (breakfast, lunch and dinner) and three separate snacks (mid-morning, mid-afternoon and evening) for users to follow throughout the day as shown in Figure 1b. A complete 'library' of 24-h meal plans was collated between experts from all EU countries for their respective user groups and subsequently integrated into the system. The AI recommender system only recommends meals from the set of meals developed by the nutrition experts. This was imperative to avoid any suggestions that may be nutritionally inappropriate for particular user groups, specifically for subgroups under medical supervision. Each plan was labelled utilising the same coding system within the Nutrium dashboard (Nutrium, 2022); *EUPartnerName-UserGroupCoding-Kcal-IndexNumber* (e.g. UniversityofSurrey-C1-1800-52). A total of 450 24-h meal plans (2173 individual meals) were created and integrated within the system using the Nutrium dashboard, two examples of which are presented in Table 5.

Finally, user-friendly meal titles were devised that could be easily read by the user on a mobile screen. All meal titles were revised to be (i) short in length to allow for display in the mobile app (40 characters including spaces), and (ii) clear as to the specific meal description. In addition, and to improve the user experience, recipes were also provided for the lunch and dinner meals, where more than basic preparation of foods was required. This additional information was provided in the home dashboard to improve engagement with the meal recommendations. Recipes were created via a 'mix and match' approach from a set of agreed steps (shown in Figure 5) to ensure standardisation across each consortium partner's meal library. These were developed within a spreadsheet whereby all experts would specify the (a) food preparation, (b) cooking method, (c) whether it is needed to be combined with other ingredients, (d) duration of cooking, (e) how to serve and (f) seasoning suggestions for each individual meal. Following this, recipes and meal titles were all translated into the languages required by users of the *PROTEIN* app by native speakers within the consortium. Recipes were not created for any meals or snacks that only required 'warming' or 'basic preparation' as it was agreed that the preparation method was sufficiently clear within the meal title. An example of this would be most breakfast meals, such as UoS-C1-1800-52 with the meal title 'Porridge, apricot, pumpkin seeds & honey' and the ingredients porridge oats, milk, pumpkin seeds, apricots and honey. This would not require a recipe as most users

TABLE 5 Example of two meal plans devised for the PROTEIN project users in Belgium (KUL-C4-1300-69) and the United Kingdom (UoS-C1-1800-52).

Template name	Meal type	Meal plan template	Meal title
KUL-C4-1300-69	Breakfast	Cereals, Milk, Seeds, Figs	Oats with fruit and seeds
	Morning snack	Strawberries, Blackberries	Berries
	Lunch	Beetroot, Salmon, Potatoes, Soup	Soup, Salmon with vegetables & potatoes
	Afternoon snack	Bananas, Crackers	Bananas, Crackers
	Dinner	Bread, Turkey slices, Avocado, Rocket, Tomatoes	Sandwich with turkey slices and vegetables
	Evening snack	Yogurt	Yogurt
UoS-C1-1800-52	Breakfast	Porridge oats, Milk, Apricots, Pumpkin seeds, Honey	Porridge, apricot, pumpkin seeds & honey
	Morning snack	Wild West Beef Jerky	Beef Jerky
	Lunch	Turkey, Pepper, Vegetables, Cheese, Salad	Stuffed peppers with turkey, salad
	Afternoon snack	Bananas	Banana
	Dinner	Chicken, Cheese spread, Tomatoes, Spinach, Stock cubes, Garlic, Onions, Basil, Cauliflower, Fat spread, Milk, Broccoli, Yogurt	Chicken, broccoli, cauliflower mash
	Evening snack	Cereal bars	Cereal bar

would anticipate that these ingredients simply require mixing, or preparing according to packet instructions, to produce the breakfast meal recommended.

DISCUSSION

This paper describes the development of a library of evidence-based, expert-approved, conceptual 'rules' for physical activity and nutrition, which were crucial to underpin an automated personalised system. This wealth of knowledge has been collated by reviewing and amalgamating applicable recommendations published by well-reputed governing bodies, such as EFSA and WHO, of direct geographical and scientific relevance to the *PROTEIN* target audience. This work represents the combined efforts and expert knowledge of the multidisciplinary team, including nutritionists/dieticians, physiologists and physical activity specialists. Recommendations for clinical populations with CVD or T2DM were produced by utilising expert-specific knowledge and consulting relevant advisory bodies such as the European Society of Cardiology (ESC). Furthermore, this work has been instrumental in aiding the development of a novel nutrition and physical activity ontology (NAct) (Tsatsou et al., 2021), which was designed to drive personalised nutrition and physical activity recommendations in the app through an AI advisor. Additional novelty is conferred by the translation of the expert knowledge base into seven languages and the inclusion of culturally appropriate foods and recipes, thereby offering an EU-applicable yet-localised app. This personalised system was tested across the EU from 2019 to 2023 and some provisional data have been presented on the appropriateness and effectiveness of the advice delivered by the system (Decorte et al., 2023; Hart et al., 2024; Wilson-Barnes, 2023). However, work is currently ongoing on examining the effects of the *PROTEIN* app on health outcomes and the overall user experience in different population groups.

Due to a lack of commercially exploitable meal databases, the experts devised a large group of meal plan templates utilising a commercially available dashboard; Nutrium (2022). They also devised a set of associated recipes to make the recommendations more user friendly, both of which have been directly integrated within the AI recommendation engine (*PROTEIN* AI advisor) of the *PROTEIN* app. The recommendation engine consisted of two layers; (a) a qualitative layer for verifying the ingredient appropriateness (this layer generated the set of appropriate meals for a user based on their user profile information) and (b) an optimisation method for generating daily and weekly dietary meal plans based on target nutrition values and ranges obtained from the expert knowledge base (Stefanidis et al., 2022). Overall, through this work, the consortium has provided personalised nutrition and lifestyle targets, of relevance to the EU population, which will support users to achieve a healthier lifestyle through their smartphones. A recent study explored how the users perceived the overall usability of this novel app and how this tied in with their behaviour change from

(a)

Amount	How to cook	Season/Mix	Method
Weighed (as above) One handful Once cup 1 tablespoon 1 teaspoon 1 pack ½ pack Whole Halved Quarters **Cook until** Cook through Until golden Until charred Until soft Al dente Cook to preference	Follow instructions on packaging Grill (no oil) Grill (lightly oiled) Boiled in unsalted water Boiled in salted water Steam Poach Oven roast (lightly oiled) Fry (no oil) Pan cook in butter Bake Raw Mix Add to pan Stir fry Toast Warm through Heat-up	Season with pinch of salt Season with grind of salt & pepper Season with a drizzle of olive oil Drain Chop & add herbs Sprinkle on herbs Mix in herbs Add sauce Spread on top Butter or low-fat spread Add dressing Drain & mash with butter or seasoning Mix in blender	Drain Boil in unsalted water Wash & chop Wash & slice Drain & add or heat Steam Add to pan Pour over Heat & pour over Grate on top Peel & slice Stir fry Served with Fry & add Bake Chop

Initial Preparation	Combine	Cooking Duration	Serve
Remove from packaging Remove skin Peel skin Skin on Wash in cold water Drain Cut stem Rub with oil & seasoning **Cut** Whole Into cubes Into slices Into wedges Into pieces Dice finely In half Grate Peel into ribbons	Mix together Pour on top Serve separately Stack Wrap Create sandwich Add water & stir Green salad **Cook** Simmer in Pan Stew in saucepan with lid Casserole in pot with lid Oven roast Grill Heat through Stir fry	5 minutes 15 minutes 25 minutes 35 minutes 45 minutes 1 hour 1 hour 30 minutes 2 hours + N/A **Side dish** Bread & butter Glass of milk Potato salad Garlic bread **Last Step** Drain pasta Drain rice Wash salad Grate cheese Mix in herbs Mix salad & dressing	On a single plate In a bowl Eat with hands Garnish Add herbs Drizzle on olive oil Add croutons Add herbs & oil Add dressing Pinch of salt Pinch of salt & pepper Add gherkins Add gherkins & mayo N/A Serve with sour cream Garnish with mustard

(b)

Evening meal title	Bass, Rice, Pak Choi, Soy Sauce, Cabbage, Carrots, Onions
New meal title (user friendly)	Sea Bass & Rice Stir Fry
Food # 1	Bass, sea, flesh only, baked
Food # 2	Rice, brown, basmati
Food # 3	Pak Choi, steamed, whole
Food # 4	Cabbage, red, raw
Food # 5	Carrots, old, raw
Food # 6	Soy sauce, light & dark varieties
Method generated	Bass, sea flesh only, baked, *cook through* Rice, brown, basmati, *boiled in unsalted water*, *cook until soft* Pak choi, steamed, whole stir fry *cook al dente* Cabbage, red, raw, *stir fry* Carrots, old, raw, *stir fry* Soy sauce, light & dark varieties, *stir fry* *Combine*: mix together *Serve*: in a bowl

FIGURE 5 (a) Example of the meal cooking and preparation options for each ingredient within a meal and (b) An existing single-meal method within the PROTEIN system (ID: UoS-B1-1200-03) created by combing the relevant steps in a.

feedback received via an online survey of over 80 individual users following a month of app usage (Balula Dias et al., 2022). It was found that the app was a supportive tool for helping users improve their lifestyle and dietary habits. However, whether the behaviour changes suggested by the app across the multiple user groups across the EU were adopted and what the drivers of food choice were within those groups will be further explored by the *PROTEIN* consortium.

A limitation of the system described within this paper is the limited number of unique meals and meal plans available. Despite the development of over 2000 separate meals, the application of filters, driven by the user profile (e.g. goals, food intolerance and dietary patterns), means that most users are offered only a small sub-sample of this total number and in some cases, variety and cultural diversity was limited. This was specifically the case for users with complex requirements such as those requiring both a vegetarian and gluten-free diet. A simple solution proposed by the experts to generate more variation across the same meals would be to provide an option for substitution within meals for equivalents of certain foods thereby providing further personalisation but also variety to all user groups. This would allow elements of the same 'base' meal to be substituted according to the user's preferences using a simple substitution function within the application. For example, where white basmati rice is suggested as part of a meal, the user could substitute the 100 g of rice with one of a selection of nutritionally equivalent grains such as 67 g of quinoa, couscous or even plain pasta, instantly expanding the number of meal options and allowing for greater real-time personalisation. While this was not possible within the current project, future personalised nutrition mobile applications should consider incorporating such an 'equivalents model' into their meal plan recommender to potentially improve meal variety and therefore user engagement and satisfaction. In addition, future nutrition mobile applications should also consider developing meal plans that also account for socio-economic status, seasonality of food availability and environmental and sustainability concerns. These aspects were not covered within the scope of this system and therefore could be a limiting factor towards user engagement.

A key strength of the *PROTEIN* app is that it was developed to cover multiple population groups, rather than just the healthy population, and as such builds on previous work, such as the pan-European *Food4Me* randomised controlled dietary intervention study (which excluded individuals with any metabolic disease or conditions altering nutritional requirements and any food intolerances/allergies) to investigate the development of more 'real-world' applications cognisant of the complex health backgrounds and dietary patterns of many EU residents.

In conclusion, members of the *PROTEIN* consortium have compiled a library of conceptual 'rules' and 'targets' for PA and dietary intake which were crucial in underpinning the *PROTEIN* mobile app system. This wealth of knowledge has been collated by reviewing and amalgamating the applicable recommendations published by well-reputed governing bodies, prioritising according to UG needs and adapting for integration into a recommender system. It is hoped that future tools will consider harnessing a similar methodology to that presented here. The nutrition and activity ontology (NAct), NAP database, user requirements and evaluation survey are all publicly available datasets on GitHub Tsatsou et al. (2021) and Zenodo Community (2024) respectively. Future research is encouraged to incorporate tailored advice according to genetic predisposition, where the evidence base supports this, to provide food equivalents for meal recipes to increase variety and to ensure the underpinning advice continues to represent the state of the art in the relevant country and/or population group.

ACKNOWLEDGEMENTS

This project has received funding from the European Union's Horizon 2020 research and innovation programme, under project number 817732. The authors would also like to thank and acknowledge all members of the *PROTEIN* consortium for their contributions towards the project.

FUNDING INFORMATION

This research received funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement 817732 (PROTEIN: personalised nutrition for healthy living).

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

ORCID

S. L. Wilson-Barnes https://orcid.org/0000-0001-9945-4800
E. Patra https://orcid.org/0000-0002-8615-1541

REFERENCES

Aldubayan, M.A., Pigsborg, K., Gormsen, S.M.O., Serra, F., Palou, M., Mena, P. et al. (2022) Empowering consumers to PREVENT diet-related diseases through OMICS sciences (PREVENTOMICS): protocol for a parallel double-blinded randomised intervention trial to investigate biomarker-based nutrition plans for weight loss. *BMJ Open*, 12, e051285.

Avram, R., Tison, G.H., Aschbacher, K., Kuhar, P., Vittinghoff, E., Butzner, M. et al. (2019) Real-world heart rate norms in the Health eHeart study. *NPJ Digital Medicine*, 2, 58.

Balula Dias, S., Oikonomidis, Y., Diniz, J.A., Baptista, F., Carnide, F., Bensenousi, A. et al. (2022) Users' perspective on the AI-based smartphone PROTEIN app for personalised nutrition and healthy living: a modified technology acceptance model (mTAM) approach. *Frontiers in Nutrition*, 9, 898031.

Barber, T.M., Kabisch, S., Pfeiffer, A.F.H. & Weickert, M.O. (2020) The health benefits of dietary fibre. *Nutrients*, 12(10), 3209.

Battelino, T., Danne, T., Bergenstal, R.M., Amiel, S.A., Beck, R., Biester, T. et al. (2019) Clinical targets for continuous glucose monitoring data interpretation: recommendations from the international consensus on time in range. *Diabetes Care*, 42(8), 1593–1603.

Bilionis, I., Apostolidis, G., Charisis, V., Liatsos, C. & Hadjileontiadis, L. (2021) Non-invasive detection of bowel sounds in real-life settings using spectrogram zeros and autoencoding. In: *2021 43rd Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC)*. Institute of Electrical and Electronics Engineers: IEEE, pp. 915–919.

Buysse, D.J. (2014) Sleep health: Can we define it? does it matter? *Sleep*, 37(1), 9.

Cashman, K., Dowling, K., Škrabáková, Z., Gonzalez-Gross, M., Valtueña, J., de Henauw, S. et al. (2016) Vitamin D deficiency in Europe: pandemic? *The American Journal of Clinical Nutrition*, 103(4), 1033–1044.

Celis-Morales, C., Livingstone, K.M., Marsaux, C.F.M., Forster, H., O'Donovan, C.B., Woolhead, C. et al. (2015) Design and baseline characteristics of the Food4Me study: a web-based randomised controlled trial of personalised nutrition in seven European countries. *Genes & Nutrition*, 10(1), 1–13.

Celis-Morales, C., Livingstone, K.M., Marsaux, C.F.M., Macready, A.L., Fallaize, R., O'Donovan, C.B. et al. (2017) Effect of personalised nutrition on health-related behaviour change: Evidence from the Food4Me European randomised controlled trial. *International Journal of Epidemiology*, 46(2), 578–588.

Chaput, J.P., Grey, C.E., Poitras, V.J., Carson, V., Gruber, R., Birken, C.S. et al. (2017) Systematic review of the relationships between sleep duration and health indicators in the early years (0-;4 years). *BMC Public Health*, 17(Suppl 5), 855.

Chaput, J.P., Grey, C.E., Poitras, V.J., Carson, V., Gruber, R., Olds, T. et al. (2016) Systematic review of the relationships between sleep duration and health indicators in school-aged children and youth. *Applied Physiology, Nutrition, and Metabolism*, 41(6 Suppl 3), S266–S282.

Cosentino, F., Grant, P.J., Aboyans, V., Bailey, C.J., Ceriello, A., Delgado, V. et al. (2020) 2019 ESC Guidelines on diabetes, pre-diabetes, and cardiovascular diseases developed in collaboration with the EASD. *European Heart Journal*, 41(2), 255–323.

Danne, T., Nimri, R., Battelino, T., Bergenstal, R.M., Close, K.L., DeVries, J.H. et al. (2017) International Consensus on use of continuous glucose monitoring. *Diabetes Care*, 40(12), 1631–1640.

Decorte, E., Wilson Barnes, S., Hart, K., Stefanidis, K., Gymnopoulos, L., Rouskas, K. et al. (2023) A pilot trial guiding development and investigating feasibility and usability as well as preliminary effectiveness of the PROTEIN application: personalised nutrition for healthy living. *European Journal of Preventive Cardiology*, 30(Supplement_1). Available from: https://doi.org/10.1093/eurjpc/zwad125.220

Diabetes. (2022) World Health Organisation. Available from: https://www.who.int/health-topics/diabetes#tab=tab_1 [Accessed 7 Mar 2022].

Donnelly, J.E., Blair, S.N., Jakicic, J.M., Manore, M.M., Rankin, J.W. & Smith, B.K. (2009) American College of Sports Medicine Position Stand. Appropriate physical activity intervention strategies for weight loss and prevention of weight regain for adults. *Medicine and Science in Sports and Exercise*, 41(2), 459–471.

EFSA. (2012) Scientific Opinion on Dietary Reference Values for protein. *EFSA Journal*, 10(2), 2557.

EFSA. (2010) Scientific Opinion on Dietary Reference Values for carbohydrates and dietary fibre. *EFSA Journal*, 8(3), 1462.

EFSA. (2017) Dietary Reference Values for nutrients Summary report. *EFSA Supporting Publications*, 14(12), e15121E.

Evert, A.B., Boucher, J.L., Cypress, M., Dunbar, S.A., Franz, M.J., Mayer-Davis, E.J. et al. (2014) Nutrition therapy recommendations for the management of adults with diabetes. *Diabetes Care*, 37(Suppl 1), S120–S143.

FAO. (2020) *Fruit and vegetables – your dietary essentials. The International Year of Fruits and Vegetables, 2021, background paper*. Rome: FAO. Available from: https://www.fao.org/3/cb2395en/online/src/html/fruit-and-vegetables.html. Accessed: 26/10/2021.

Hart, K., Wilson-Barnes, S., Lanham-New, S.A. & Gymnopoulos, L. (2024) Can a mobile application deliver appropriate, acceptable and usable personalised nutrition advice to UK adults. *Proceedings of the Nutrition Society*, 82(OCE5), E314.

Isak – The International Society for the Advancement of Kinanthropometry. (2022) Available from: https://www.isak.global/ [Accessed 8 Mar 2022].

Kasper, A.M., Langan-Evans, C., Hudson, J.F., Brownlee, T.E., Harper, L.D., Naughton, R.J. et al. (2021) Come back skinfolds, all is forgiven: a narrative review of the efficacy of common body composition methods in applied sports practice. *Nutrients*, 13(4), 1075.

König, L.M., Attig, C., Franke, T. & Renner, B. (2021) Barriers to and facilitators for using nutrition apps: systematic review and conceptual framework [published online ahead of print, 2021 Apr 1]. *JMIR mHealth and uHealth*, 9(6), e20037.

Konstantinidis, D., Dimitropoulos, K., Langlet, B., Daras, P. & Ioakimidis, I. (2020) Validation of a deep learning system for the full automation of bite and meal duration analysis of experimental meal videos. *Nutrients*, 12(1), 209.

Lopez, P., Taaffe, D.R., Galvão, D.A., Newton, R.U., Nonemacher, E.R., Wendt, V.M. et al. (2022) Resistance training effectiveness on body composition and body weight outcomes in individuals with overweight and obesity across the lifespan: a systematic review and meta-analysis. *Obesity Reviews*, 23(5), e13428.

Medic, G., Wille, M. & Hemels, M.E.H. (2017) Short- and long-term health consequences of sleep disruption. *Nature and Science of Sleep*, 9, 151.

Meeusen, R., Duclos, M., Foster, C., Fry, A., Gleeson, M., Nieman, D. et al. (2013) Prevention, diagnosis and treatment of the overtraining syndrome: joint consensus statement of the European College of Sport Science (ECSS) and the American College of Sports Medicine (ACSM). *European Journal of Sport Science*, 13(1), 1–24.

Mullins, V.A., Bresette, W., Johnstone, L., Hallmark, B. & Chilton, F.H. (2020) Genomics in personalised nutrition: can you "Eat for Your Genes"? *Nutrients*, 12(10), 3118. Available from: https://doi.org/10.3390/nu12103118

Nutrium. (2022) Nutrium | Nutrition Software. Available from: https://nutrium.com/en?utm_source=google&utm_medium=cpc&utm_campaign=UK_IE_Search_Brand&utm_content=UK_IE_Nutrium_Exact&utm_term=nutrium&gclid=CjwKCAiA4KaRBhBdEiwAZi1zzqJlgi_gw87VUzNSzdOpMLMEmY0hamFwzWiqnv9XLyXrFY0do5UG9BoC1soQAvD_BwE [Accessed 10 Mar 2022].

Oh, H., Kim, H., Lee, D., Lee, A., Giovannucci, E., Kang, S. et al. (2019) Different dietary fibre sources and risks of colorectal cancer and adenoma: a dose–response meta-analysis

of prospective studies. *British Journal of Nutrition*, 122(6), 605–615. Available from: https://doi.org/10.1017/S0007114519001454
Piepoli, M.F., Hoes, A.W., Agewall, S., Albus, C., Brotons, C., Catapano, A.L. et al. (2016) 2016 European Guidelines on cardiovascular disease prevention in clinical practice. The Sixth Joint Task Force of the European Society of Cardiology and Other Societies on Cardiovascular Disease Prevention in Clinical Practice (constituted by representatives of 10 societies and by invited experts) Developed with the special contribution of the European Association for Cardiovascular Prevention & Rehabilitation (EACPR). *European Heart Journal*, 37(29), 2315–2381.
Pintér, Z., Pósa, A., Varga, C., Horváth, I., Palkó, A., Just, Z. et al. (2017) Anthropometric dimensions provide reliable estimates of abdominal adiposity: a validation study. *Homo: internationale Zeitschrift fur die vergleichende Forschung am Menschen*, 68(5), 398–409.
Public Health England. (2018) The Eatwell Guide. Available from: https://www.gov.uk/government/publications/the-eatwell-guide [Accessed 13 Nov 2019].
Reynolds, A.N., Akerman, A., Kumar, S., Diep Pham, H.T., Coffey, S. & Mann, J. (2022) Dietary fibre in hypertension and cardiovascular disease management: systematic review and meta-analyses. *BMC Medicine*, 20, 139.
Rydén, L., Grant, P.J., Anker, S.D., Berne, C., Cosentino, F., Danchin, N. et al. (2013) ESC Guidelines on diabetes, pre-diabetes, and cardiovascular diseases developed in collaboration with the EASD: the Task Force on diabetes, pre-diabetes, and cardiovascular diseases of the European Society of Cardiology (ESC) and developed in collaboration with the European Association for the Study of Diabetes (EASD). *European Heart Journal*, 34, 3035–3087.
Scientific Advisory Committee on Nutrition (2019) Vitamin D and health report. Available online: https://assets.publishing.service.gov.uk/media/5a804e36ed915d74e622dafa/SACN_Vitamin_D_and_Health_report.pdf. Accessed on 01 March 2023.
Shan, Z., Ma, H., Xie, M., Yan, P., Guo, Y., Bao, W. et al. (2015) Sleep duration and risk of type 2 diabetes: a meta-analysis of prospective studies. *Diabetes Care*, 38(3), 529–537.
Shen, X., Wu, Y. & Zhang, D. (2016) Nighttime sleep duration, 24-hour sleep duration and risk of all-cause mortality among adults: a meta-analysis of prospective cohort studies. *Scientific Reports*, 6, 21480.
Smartphone market in Europe. (2023) Statista. Available from: https://www.statista.com/topics/3341/smartphone-market-in-europe/#topicOverview [Accessed 11 Jan 2023].
Stefanidis, K., Tsatsou, D., Konstantinidis, D., Gymnopoulos, L., Daras, P., Wilson-Barnes, S. et al. (2022) PROTEIN AI advisor: a knowledge-based recommendation framework using expert-validated meals for healthy diets. *Nutrients*, 14(20), 4435.
St-Onge, M.P., Grandner, M.A., Brown, D., Conroy, M.B., Jean-Louis, G., Coons, M. et al. (2016) Sleep duration and quality: impact on lifestyle behaviours and cardiometabolic health: a scientific statement from the American heart association. *Circulation*, 134(18), e367–e386.
Stubbs, B., Vancampfort, D., Smith, L., Rosenbaum, S., Schuch, F. & Firth, J. (2018) Physical activity and mental health. *The Lancet. Psychiatry*, 5(11), 873.
Theodoridis, T., Solachidis, V., Dimitropoulos, K. & Daras, P. (2020) A cross-modal variational framework for food image analysis. In: *2020 IEEE International Conference on Image Processing (ICIP)*. Institute of Electrical and Electronics Engineers: IEEE, pp. 3244–3248.
Tsatsou, D., Lalama, E., Wilson-Barnes, S., Hart, K., Cornelissen, V., Buys, R. et al. (2021) NAct: the nutrition & activity ontology. *GitHub*. Available from: https://nutritionactivityontology.github.io/nact/ [Accessed 10 Mar 2022].
United States Department of Agriculture (USDA). (2019) ChooseMyPlate. Available from: https://www.choosemyplate.gov/ [Accessed 13 Nov 2019].
Vanderwall, C., Randall Clark, R., Eickhoff, J. & Carrel, A.L. (2017) BMI is a poor predictor of adiposity in young overweight and obese children. *Pediatrics*, 17, 135.
Vanhees, L., Rauch, B., Piepoli, M., van Buuren, F., Takken, T., Börjesson, M. et al. (2012) Importance of characteristics and modalities of physical activity and exercise in the management of cardiovascular health in individuals with cardiovascular disease (Part III). *European Journal of Preventive Cardiology*, 19(6), 1333–1356.
Veronese, N., Solmi, M., Caruso, M.G., Giannelli, G., Osella, A.R., Evangelou, E. et al. (2018) Dietary fibre and health outcomes: An umbrella review of systematic reviews and meta-analyses. *American Journal of Clinical Nutrition*, 107, 436–444.
Wang, D., Li, W., Cui, X., Meng, Y., Zhou, M., Xiao, L. et al. (2016) Sleep duration and risk of coronary heart disease: A systematic review and meta-analysis of prospective cohort studies. *International Journal of Cardiology*, 219, 231–239.
Wang, Y., Mei, H., Jiang, Y.R., Sun, W.Q., Song, Y.J., Liu, S.J. et al. (2015) Relationship between duration of sleep and hypertension in adults: a meta-analysis. *Journal of Clinical Sleep Medicine*, 11(9), 1047–1056.
Weickert, M.O. & Pfeiffer, A.F.H. (2018) Impact of dietary fibre consumption on insulin resistance and the prevention of type 2 diabetes. *The Journal of Nutrition*, 148(1), 7–12.
WHO. (2011) Waist circumference and waist–hip ratio. *WHO Expert*, 64(1), 2–5.
Wilson-Barnes, S. (2023) The evaluation of a personalised nutrition and physical activity tool to facilitate lifestyle changes for adults with poor-quality diets. *Proceedings of the Nutrition Society*, 82(OCE1), E42.
Wilson-Barnes, S., Gymnopoulos, L.P., Dimitropoulos, K., Solachidis, V., Rouskas, K., Russell, D. et al. (2021) Personalised nutrition for healthy living: The PROTEIN project. *Nutrition Bulletin*, 46(1), 77–87.
World Health Organisation. (2022a) WHO guidelines on physical activity and sedentary behaviour. Available from: https://www.who.int/publications/i/item/9789240015128 [Accessed 9 Mar 2022].
World Health Organisation. (2022b) Global recommendations on physical activity for health. Available from: https://www.who.int/publications/i/item/9789241599979 [Accessed 9 Mar 2022].
Wu, Y., Zhai, L. & Zhang, D. (2014) Sleep duration and obesity among adults: a meta-analysis of prospective studies. *Sleep Medicine*, 15(12), 1456–1462.
Zenodo Community. (2024) Protein H2020 Project. Available from: https://zenodo.org/communities/protein-h2020-project?q=&l=list&p=1&s=10&sort=newest [Accessed 21 January 2024].
Zhai, L., Zhang, H. & Zhang, D. (2015) Sleep duration and depression among adults: a meta-analysis of prospective studies. *Depression and Anxiety*, 32(9), 664–670.

How to cite this article: Wilson-Barnes, S.L., Pagkalos, I., Patra, E., Kokkinopoulou, A., Hassapidou, M., Lalama, E. et al. (2024) The development of an EU-wide nutrition and physical activity expert knowledge base to support a personalised mobile application across various EU population groups. *Nutrition Bulletin*, 49, 220–234. Available from: https://doi.org/10.1111/nbu.12673