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Exploration of strategic food vehicles for vitamin D fortification in low/lower-middle income countries

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ABSTRACT

We previously identified 7 low/lower-middle income countries (LMICs; Afghanistan, Pakistan, India, Mongolia, Yemen, Nigeria, Tunisia) which have excess burden of vitamin D deficiency and could benefit enormously from food fortification with vitamin D. A key challenge is finding a suitable industrially-manufactured food vehicle that is consumed in sufficient amounts by the population at-risk. We used FAO Food Balance Sheet data (from 2003-2013) to model the potential impact of four different food vehicles (edible plant-based oil, wheat flour, maize flour, and milk), and at different addition levels, on the average per capita vitamin D supply in all 7 LMICs. Daily per capita supply for ˜95 foods was calculated and vitamin D supply determined using dietary analysis software with no addition and following stepwise additions of vitamin D to the four food vehicles. The daily per capita vitamin D supply without fortification ranged from 0.4 to 3.3 μg (≤2 μg/d in six LMICs). We applied a vitamin D intake of 5 μg/d as a benchmark because it maintains serum 25-hydroxyvitamin D ≥ 25 nmol/L in ˜90% of individuals. Modelling showed that fortifying edible oil with vitamin D at the 7.5 μg/100 g (guideline) and 15 μg/100 g levels allowed vitamin D supply in 1 and 3 of the 7 LMICs, respectively, to attain ≥5 μg/d (range: 5.8–11.0 μg/d). Fortifying milk at the 1.0 μg/100 g and 2.0 μg/100 g guideline levels, allowed 2 and 3 LMICs, respectively, to attain ≥5 μg/d (range: 5.2–9.8 μg/d). Fortifying wheat flour at the 1.4 μg/100 g (guideline) and 2.8 μg/100 g allowed 5 and 6 LMICs, respectively, to attain ≥5 μg/d (range: 5.3–18.6 μg/d). Maize flour had low impact due to consumption levels. In conclusion, using these levels of addition, at least one food vehicle was able to increase per capita vitamin D supply to ≥5 μg/d in each of the LMICs.

1. Introduction

While there has been considerable and on-going emphasis placed on the issue of vitamin D deficiency in the higher income country setting, in recent years there has been growing concern about vitamin D deficiency as a possible public health concern in low- and lower-middle income countries (LMICs). Several systematic literature reviews (SLRs) of global vitamin D status [1,2], as well as our recent LMIC-focussed SLR [3], highlight the general lack of available data on prevalence of vitamin D status for the majority of LMICs. It is of note, however, that where such data does exist, several LMICs have been consistently shown to have extremely high and worrisome estimates of the prevalence of low vitamin D status [1–3], potentially putting the health and wellbeing of significant numbers of individuals within these populations at risk. These reported prevalence estimates in many cases far exceed the suggested guide of where more than 20% of the population (overall, or within identifiable subgroups) has circulating 25-hydroxyvitamin D (25(OH)D) concentrations < 25/30 nmol/L, public health intervention should be considered [4]. Of particular concern, within the LMICs, infants, young children and women of child-bearing age were shown to be at highest risk [2,3], subgroups of the population which the World Health Organisation (WHO) emphasise in terms of ensuring adequate nutrition [5,6].

In terms of public health interventions that could be considered to address the excess prevalence of vitamin D deficiency in these LMICs, the World Health Organisation-Food and Agriculture Organization (WHO-FAO) have indicated that of the four key strategies for the control of micronutrient malnutrition, food fortification is the preferred approach in terms of sustainability, uptake and cost-effectiveness [7]. The *Global Fortification Data Exchange* has recently suggested that two-thirds of all countries mandate food fortification to combat micronutrient malnutrition, yet many are not necessarily translating policy

Abbreviations: 25(OH)D, 25-hydroxyvitamin D; FAO, Food and Agriculture Organisation; FBS, Food balance sheets; FDA, Food and Drug Administration; LMICs, Low and lower-middle income countries; SLR, Systematic literature review; WHO, World Health Organisation

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into improved nutrition [8]. They suggest food fortification could be the next global health success story – if countries close the gaps [8]. Thus, food fortification with vitamin D could have enormous impact in the at-risk LMICs, once done effectively. The WHO-FAO stress that a key challenge is finding a suitable, culturally appropriate, industrially-manufactured food vehicle that is consumed in sufficient amounts by the populations at-risk [7]. Black et al. [9] have also suggested that beyond the range of food vehicles used for fortification, careful consideration must also be given to the concentration of vitamin D used in each to optimize the effectiveness and minimize risk of excessive intakes. While this can be achieved by modelling usual food consumption intakes in representative populations [7,9], there is a dearth of intake data in LMICs [3,4]. In the absence of such data, we have recently shown that estimates of average per capita supply of vitamin D in LMICs, as calculated using information from FAO Food Balance Sheets (FBS), may be of use as proxy measures for vitamin D intake within the population [3].

The objective of the present work was to use data from FAO-FBS to model the potential impact of vitamin D fortification of four different priority food vehicles (edible plant-based oil, wheat flour and maize flour, and milk) on the average per capita vitamin D supply in a select number of LMICs which have excess burden of vitamin D deficiency and could benefit enormously from food fortification with vitamin D. Various levels of addition of vitamin D were tested for each vehicle and these were informed by relevant international or national food standards or guidelines.

2. Materials and methods

2.1. Selection of seven LMICs for FAO Food Balance Sheet data modelling

As mentioned above, we recently conducted a comprehensive SLR of published data on vitamin D deficiency in the 83 World Bank Group-designated LMICs for 2017 [3]. Only 35% of these LMICs had published data on vitamin D status suitable for inclusion, and of these, we identified 5 LMICs (Afghanistan, India, Mongolia, Pakistan, Tunisia) with consistent evidence of excess burden of vitamin D deficiency [3], defined as prevalence of serum 25(OH)D < 25/ < 30 nmol/L in excess of greater than 20% at a population-level and/or within vulnerable subgroups of the population (infants, children, women of reproductive age, pregnant women) [4]. There were an additional 4 LMICs which we designated as potentially having excess burden (Syria, Nigeria, Yemen, West Bank & Gaza) on the basis that only one included study was available for each country but the prevalence data within same met with the above definition [3]. In the present work, we performed update structured electronic searches for these 4 countries, which showed no new papers for Syria or Yemen. Of those papers for Nigeria and West Bank & Gaza published since May 18th 2017 (date of the final screen within our original SLR) [10–14], none were considered to report data that would change our original designation of these 4 LMICs [3]. For currency, we also downloaded and cross-checked the most recent listing of LMICs from the World Bank Group (i.e., 2019 fiscal year) [15], and performed electronic searches for the two new countries (Angola and Georgia), which yielded no studies with data on vitamin D status for either. Finally, of our list of 9 LMICs with/likely to have excess burden of vitamin D deficiency, FAO-FBS data was available for 7 of these (data was not available for Syria or West Bank & Gaza). Thus, our vitamin D food fortification modelling of FAO-FBS data was undertaken for Afghanistan, India, Mongolia, Nigeria, Pakistan, Tunisia, and Yemen.

2.2. Estimation of daily per capita vitamin D supply in the 7 selected LMICs using FAO Food Balance Sheet data

The per capita vitamin D supply was estimated using FAO-FBS, as outlined in detail elsewhere [16]. In brief, yearly FBS for the period 2003–2013 were downloaded as csv files from the FAOSTAT database [17] for each of the 7 LMICs. The most recently added food balance sheet data within the FAOSTAT database is for 2013. The sheets provided overall per capita supply data (as kg/year) for 17 food commodity groupings, which were coded in their most unprocessing form and entered into WISP© nutritional analysis software (Tinuviel Software, Anglesey, UK), which incorporates the UK food compositional database [18]. This allowed for the estimation of average per capita vitamin D supply (μg/day) over the ten-year period.

2.3. Selection of food vehicles for vitamin D fortification within FAO Food Balance Sheet data modelling

In terms of fortification, vitamin D has been successfully added to a number of lipid-rich or non-lipid-containing food vehicles [4]. The comprehensive interactive data provided by the *Global Fortification Data Exchange* in relation to food fortification highlight oil, maize flour, rice, salt and wheat flour as food vehicles used for micronutrient fortification in general [8]. Of these food vehicles, data on the number which include vitamin D within their food standards highlight oil as the most common and, to a much lesser extent, wheat flour in LMICs; whereas in high-income and upper-middle income countries, oil, wheat flour, maize flour and rice are highlighted almost with equal occurrence [19]. While the *Global Fortification Data Exchange* does not capture data on milk within its listing of food vehicles [8], it is possibly the most commonly fortified food for vitamin D in many high-income countries [4]. Thus, for the present work, four foods/commodities contained within the FBS data were considered as potential food vehicles for fortification with vitamin D in the 7 selected LMICs: i) edible plant-based oils, ii) wheat and wheat products, iii) maize, and iv) milk. The per capita daily availability of these four vehicles in all 7 LMICs, based on the most recent FAO-FBS data (i.e., 2013), are shown in Supplemental Fig. 1.

We made an assumption that all data within the FBS pertaining to wheat and wheat products in these countries were as flour and therefore available for mandatory fortification with vitamin D (see below); similarly, with maize, milk and edible plant-based oils. For the edible plant-based oils, the individual oils within the FBS were aggregated into a collective supply of all oils, forming one category in terms of modelling vitamin D fortification of (see Supplemental Information for list of individual oils).

2.4. Modelling of impact of different levels of vitamin D fortification of the four potential vehicles on per capita vitamin D supply, including assumptions made

We used data available through the *Global Fortification Data Exchange*'s interactive maps [19–21] to ascertain if any of the 3 plant-based vehicles were presently fortified with vitamin D within the LMICs. While the cereals were not fortified with vitamin D in any of the 7 LIMCs, oil was in some countries (see Supplemental Information for detail). However, due to data gaps in relation to the proportion of oil that is fortified in each case, we used the per capita average supply of vitamin D using FAO-FBS data (outlined above) without trying to account for oil fortification. These estimates were used as an index of the typical dietary supply of vitamin D (and as base dietary data) in the 7 LMICs.

Per capita vitamin D supply was then modelled using the same FAO-FBS data but following stepwise additions of vitamin D to each of the four food vehicles individually on a mandatory basis. The levels of vitamin D fortification of each of the four food vehicles are shown in Table 1. The core guidance level of vitamin D addition for each was informed by an international or national food standard/guideline as follows: For edible plant-based oils, 7.5 μg/100 g as the level recommended by the World Food Programme International Guidelines [22]; for wheat flour, 1.4 μg/100 g as the level recommended by the Gulf Cooperation Council Standardisation Organisation Regional

Table 1
Levels of vitamin D fortification of food vehicles for modelling impact of fortification on per capita vitamin D supply in the 7 LMICs.

Food vehicle	International or national food standard	Vitamin D fortification levels (μg/100 g)*
Edible plant-based oils		0
		3.8
	World Food Programme International Guideline 2011 [22]	7.5
		11.3
		15.0
Wheat flour		0
		0.7
	Gulf Cooperation Council Standardisation Organisation Regional Guidelines 2014 [23]	1.4
		2.1
		2.8
		5.0
		10
Maize flour		0
		0.7
		1.4
		2.1
		2.8
Milk		0.0
		0.5
	US Food and Drug Administration National Guideline 2016 [24]	1.0
		1.6
		2.0

* As recommended by food standard or guideline, or fractions and multiples of these.

Guidelines [23], a level we also adopted for maize flour in the absence of a standard; and for milk, 1.0 μg/100 g as the level recommended by the US Food and Drug Administration (FDA) national guideline [24]. Using an approach recently applied by Bromage et al. [25] for modelling the impact of food fortification with multiple micronutrients on their intakes among Mongolian adults, fractions and multiples of these guidelines were also applied in the modelling (Table 1). These levels of fortification were also of real-world relevance as fit within the range proposed within individual national standards in some countries [26–30] (see Supplemental Information for detail).

While the food standard for wheat flour and milk relate to fortification with vitamin D_3 [23,24], it should be noted that some national food standards permit use of vitamin D_3 and/or vitamin D_2 in certain foods [24,29]. Accordingly, in relation to fortification, we use the term vitamin D to refer to vitamin D_3 and/or vitamin D_2, depending on the food standard that pertains in a particular LMIC.

While previous modelling of the impact of vitamin D fortification of vegetable oils included an assumption of a 20% loss during processing, storage and cooking [31], such losses were not included in the present analyses on the basis that it is recommended that manufacturers add extra amounts of micronutrient (referred to as 'an overage') to account for any subsequent losses of fortificant during production, storage and distribution [7]. In the case of vitamin D, the FAO-WHO guidelines on food fortification indicate use of a 20% overage [7]. Finally, for clarity and simplicity in terms of illustration of the impact of fortification on per capita vitamin D supply, we wished to present the data on each food vehicle individually and not present as permutations of the four vehicles and different levels of vitamin D fortification.

2.5. Vitamin D intake targets for benchmarking purposes

In terms of vitamin D intake targets against which to benchmark the per capita vitamin D supply estimates generated in the present work, the Institute of Medicine in the US set 10 μg/d as the Estimated Average Requirement for vitamin D [32]. There is a considerable gap between current vitamin D intakes in many countries, especially in some LMICs, and an intake target of 10 μg/d. Vitamin D intakes of 4.7 μg/d and 7.5 μg/d have been shown to maintain serum 25(OH)D ≥ 25 nmol/L in 90% and 95% of individuals, respectively [33]. The WHO recommended intake for vitamin D for those aged 0–50 years, including pregnancy and lactation, is 5 μg/d [34]. Thus, a target intake of 5 μg/d may be an intermediate, and achievable, measure for these LMICs considering their per capita vitamin D supply is in the range of 0.6–3.3 μg/d [3].

3. Results

The estimated average per capita vitamin D supply from the base diet, based on FAO-FBS data from 2003 to 2013, for the 7 LMICs are shown in Supplemental Table 2 and Figs. 1–3. The average vitamin D supply for four out of 7 LMICs was ≤1 μg/d, was between 1 to 2 μg/d for two LMICs, and with only one LMIC (Tunisia) having > 3 μg/d. In Tunisia, the vast majority (71%) of this vitamin D supply of 3.3 μg/d came from Pelagic fish (data not shown). Milk contributed between 1.2 and 46.6% to the average per capita vitamin D supply, depending on the LMIC, whereas none of the three plant-based foods made any contribution due to their lack of, or assumed lack or, vitamin D content (data not shown).

The modelled impact of vitamin D fortification to the guideline level in milk (1.0 μg/100 g), edible plant-based oils (7.5 μg/100 g), and wheat flour (1.4 μg/100 g) on average per capita vitamin D supply is shown in Figs. 1–3, respectively. While the mandatory fortification of milk was projected to increase average daily per capita vitamin D supply by 0.2–4.2 μg over base dietary supply, depending on LMIC, all bar two (Pakistan and Tunisia at 5.2 and 5.9 μg/d, respectively) still

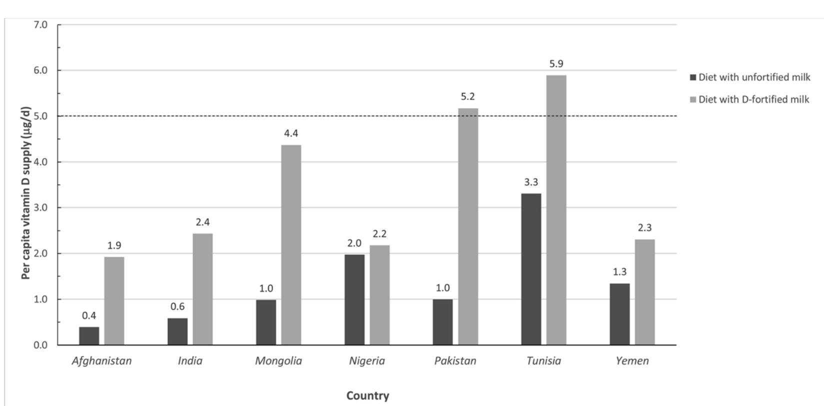

Fig. 1. The modelled impact of vitamin D fortification of milk to the guideline level (1.0 μg/100 g) on average per capita vitamin D supply in the 7 low/lower-middle income countries. Dashed line representing a per capita vitamin D supply of 5 μg/d.

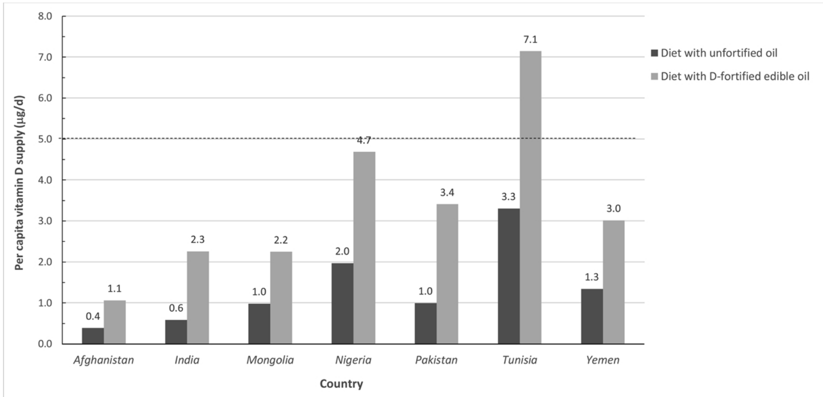

Fig. 2. The modelled impact of vitamin D fortification of edible plant-based oils to the guideline level (7.5 μg/100 g) on average per capita vitamin D supply in the 7 low/lower-middle income countries. Dashed line representing a per capita vitamin D supply of 5 μg/d.

had supply estimates < 5 μg/d. Mongolia had a per capita supply of 4.4 μg/d, and the remaining 3 LMICs had estimates of ≤2.4 μg/d following modelled fortification of milk.

While the mandatory fortification of edible plant-based oils was projected to increase average daily per capita vitamin D supply by 0.7–3.8 μg over base dietary supply, depending on LMIC, all bar one (Tunisia at 7.1 μg/d) still had supply estimates < 5 μg/d. Nigeria had a per capita vitamin D supply of 4.7 μg/d, whereas the other 5 LMICs had estimates in the range 1.1–3.4 μg/d following modelled fortification of oil.

Mandatory fortification of wheat flour was projected to increase average daily per capita vitamin D supply by 0.8–7.6 μg over base dietary supply, depending on LMIC. Of note, all bar two LMICs (India and Nigeria, each at 2.8 μg/d) had supply estimates in excess of 5 μg/d (range: 5.3–11.0 μg/d) following modelled fortification of wheat flour.

The modelled impact of vitamin D at the wheat flour guideline level (1.4 μg/100 g) to maize flour was minimal to modest (increment range of 0–1.0 μg/d over base vitamin D supply, depending on the LMIC) (data now shown). Nigeria with the 1.0 μg/d increment, still only had a per capita vitamin D supply of 3.0 μg/d following modelled fortification of maize flour.

The modelled impact of vitamin D fortification of all four food vehicles at levels fractions or multiples of the guidelines on average per capita vitamin D supply is also shown in Supplemental Table 2. Using half the guidelines levels of vitamin D fortification had only modest impact on per capita vitamin D supply, with the exception of wheat, milk and edible oil fortification in Tunisia where 7.1, 5.9 and 5.3 μg/d, respectively, were achieved. Increasing the level of vitamin D fortification to twice the vehicle-specific guideline levels (i.e., 15 μg/100 g oil, 2 μg/100 g milk, 2.8 μg/100 g wheat) led to 3, 3 and 6 LMICs, respectively, having per capita vitamin D supply estimates > 5 μg/d.

4. Discussion

Fortification of widely distributed and consumed foods has the potential to improve the nutritional status of a large proportion of the population, and neither requires changes to dietary patterns nor individual decision for compliance [35]. In the context of vitamin D, identification of such suitable, culturally appropriate, industrially-manufactured food vehicle(s) that are consumed in sufficient amounts by the populations at-risk is of high importance [7]. In addition, consideration of the appropriate level of vitamin D addition to these vehicles has been stressed in terms of effecting evidence-based food fortification programmes [9]. The present modelling work, based on data from FAO-FBS from 2003 to 2013, explored how fortification of four commonly-used food vehicles might improve the average per capita vitamin D supply, as a surrogate for intake, in 7 LMICs identified as being at risk of excess burden of vitamin D deficiency.

Milk is the most commonly fortified food for vitamin D in many high-income countries [4], but its utility in the LMIC setting is less clear. Our modelling showed that when milk was fortified with vitamin D to the guideline level, it improved per capita vitamin D supply to a variable degree amongst the 7 LMICs, such that two LMICs reached a per capita vitamin D supply of ≥5 μg/d, Mongolia reached 4.4 μg/d, whereas the remaining four LMICs had per capita vitamin D supply of ≤2.4 μg/d. Using a level of addition of twice our chosen guideline level (i.e., 2.0 μg/100 g), and consistent with the national guidelines for Canada [30], allowed three of the 7 LMICs reach a per capita vitamin D

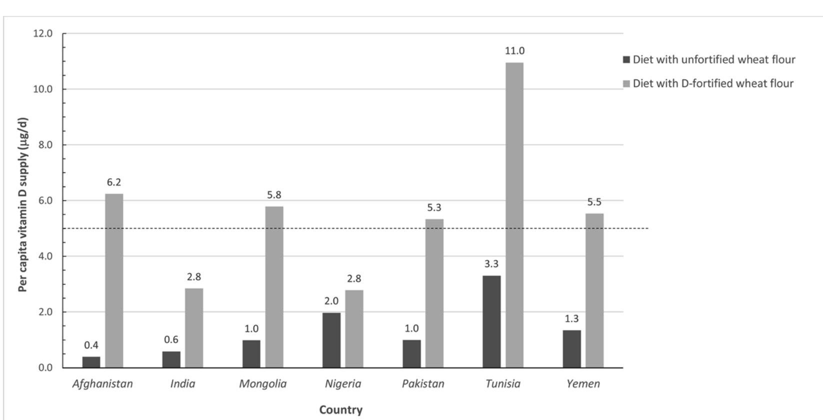

Fig. 3. The modelled impact of vitamin D fortification of wheat flour to the guideline level (1.4 μg/100 g) on average per capita vitamin D supply in the 7 low/lower-middle income countries. Dashed line representing a per capita vitamin D supply of 5 μg/d.

supply of ≥ 5 μg/d, range 8.1 to 9.8 μg/100 g. As highlighted by the WHO-FAO, the food vehicle needs to be consumed in sufficient amounts by the populations at-risk [7]. The LMICs which had least benefit from vitamin D fortification of milk (Nigeria, Yemen, Afghanistan and India) were those with the lowest per capita availability (22 to 232 g/d). India's national food standard allows for vitamin D fortification of milk at the level of 0.5-0.75 μg/100 ml [29]. Our modelling of fortification to 0.5 μg vitamin D per 100 g milk showed that average per capita vitamin D supply only increased to 1.4 μg/d in India. It has been suggested that milk may have challenges as a vehicle in some LMICs due to low availability and affordability as well as capability and technological barriers for smaller local dairy producers [4,7,25].

Vitamin D fortification of foods other than dairy products has been used as an alternative approach in countries where dairy consumption is low because of cost, intolerance, or other factors [36]. This may also take on increasing importance in light of recent international calls for more sustainable diets which have greater emphasis on plant-based foods and less in animal-based foods such as dairy and meat [37]. Data from national food standards for vitamin D highlight edible plant-based oils as the most commonly used vehicle within LMICs [19]. When the guideline level of vitamin D fortification for edible plant-based oil (7.5 μg/100 g) was modelled with the FAO-FBS data in the present work, it improved per capita vitamin D supply to a variable degree amongst the 7 LMICs, such that Tunisia again reached 7.1 μg/d, with Nigeria reaching 4.7 μg/d, whereas the remaining five LMICs had per capita vitamin D supply of ≤ 3.4 μg/d. National standards for vitamin D addition exist for 4 of the 7 LMICs, and the range of recommended level of fortification (average of min-max) was 8-15 μg/100 g [20]. Using a level of fortification at twice the guideline level (i.e., 15 μg/100 g) allowed three of the 7 LMICs reach a per capita vitamin D supply of ≥ 5 μg/d, range 5.8 to 11.0 μg/100 g. It should be noted that these projected increases in vitamin D supply are likely overestimations in some, or all, of these LMICs, as the modelling used all available plant-based edible oils for fortification, which may not be feasible in all these countries. In addition, some of these oils may have been used for cooking and thus the supply estimate may be an overestimate of intake. While it has been suggested edible oils are important candidate vehicles for fortification in many LMICs, as they are centrally processed, broadly distributed, and widely consumed by all age groups [4], data on the proportion of oil industrially processed, representing the industry's feasibility to fortify, was not available for the 7 LMICs selected for the present work [20]. This data gap limited our ability to try and account for fortification of oil with vitamin D on estimation of vitamin D supply at baseline, likely leading to these being underestimates for at least four LMICs who have mandatory or voluntary fortification.

It has been suggested that fortification of flour made from wheat and maize, when appropriately implemented, is an effective, simple, and inexpensive strategy for supplying vitamins and minerals to the diets of large segments of the world's population [35]. While these flours have been considered for fortification with iron, zinc, folic acid, vitamin B_{12} and vitamin A in LMIC due to their public health significance [35], consideration of their fortification with vitamin D is far less mature. For example, none of the 7 at-risk LMICs have vitamin D fortification of either maize flour or wheat flour in their food standards. Our modelling showed that overall, maize flour was the least effective vehicle in terms of improving per capita vitamin D supply when the guideline level for wheat flour fortification was applied, as none existed for maize itself. Even in Nigeria with the highest availability (90 g/d), fortification of maize flour at the guideline level only increased per capita vitamin D supply by a modest 1.0 μg/d. The increments in per capita vitamin D supply in the other 6 LMICs were only in the range of 0-0.5 μg/d. An interim consensus statement from 6 key Non-Government Organisations/charitable foundations suggests that while fortification of maize and wheat flour is a preventative food-based approach to improve micronutrient status of populations over time, fortification of other appropriate food vehicles should also be considered when feasible [35]. The relatively low impact of maize flour fortification with vitamin D in particular relates to the modest consumption profile, as reflected by 0–90 g/d (median, 27 g/d) of maize being available for consumption in the 7 LMICs [8]. In contrast, the equivalent estimates for wheat availability was 57–541 g/d (median, 311 g/d) [8].

Of note, fortification of wheat flour at the guideline level was shown to improve per capita vitamin D supply such that five LMICs reached a per capita vitamin D supply of ≥ 5 μg/d. Only Nigeria and India failed to meet this target with a supply of 2.8 μg/d each, and these were the two LMICs with lowest per capita availability of wheat at 57 g/d and 166 g/d, respectively. As mentioned above, Jordan and Palestine recommend a level of addition (average of min-max) of 1.45–2.3 μg/100 g [20], and the US FDA allow fortification of grain products with vitamin D at a level of 2.25 μg/100 g [26], even though flour is not contained within the definition at present. Using a level of fortification at twice the guideline level (i.e., 2.8 μg/100 g) allowed six of the 7 LMICs to reach a per capita vitamin D supply of ≥ 5 μg/d, range 5.1–18.6 μg/100 g. Again only Nigeria failed to reach this target. For other micronutrients, the interim consensus statement has guidelines which suggest higher or lower fortification levels depending on whether the national wheat availability is < 75, 75–149, 150–300 or > 300 g/d, respectively [35].

That the modelling within the present work was based on data from FBS and not quantitative food and nutrient intake data from nationally representative surveys is a limitation. The FBS only take into account the amount of food available within a country, and as such it has been suggested that nutrient intake may be overestimated owing to wastage from preparation or spoiled foods not being taken into account [38]. For vitamin D, however, there were only a few foods which contained vitamin D, and these were of animal origin and possibly less prone to wastage/spoilage. Bromage et al. [25] recently reported data on the projected effectiveness of mandatory fortification of wheat flour, milk and edible oil with multiple micronutrients, including vitamin D, among Mongolian adults. They collected six days of diet records from 320 adults and reported a mean habitual intake of vitamin D of ˜0.9 μg/d [25], very similar to that generated in the present work (1.0 μg/d) highlighting the utility of modelling the FAO-FBS data as proxy intake estimates. It should be stressed, however, that the FBS approach can't account for variations in consumption levels between genders, different population subgroups or even regional differences, such as urban versus rural. In addition, it is not feasible using this approach to generate estimates of the percentage of the population with vitamin D intakes below specified targets or above the UL in terms of safety. A number of studies which have modelled the impact of food fortification with different levels of vitamin D addition highlight the very good safety profile of fortification of milk, wheat and edible oil, as evidenced by a lack of intakes exceeding the UL [25,28,39].

In conclusion, while very cognizant of the many other complexities and considerations in terms of fortification of food within individual LMICs, and which would impact on the success or otherwise of a fortification programme, the present modelling of publically available FBS data from the FAO suggests that fortification of wheat, and, to a lesser extent, edible plant-based oil and milk, with vitamin D at levels which are currently being used within the range of international or nation standards, represents a viable means of improving current low intakes in these at-risk LMICs. Using these levels of addition, and assuming any losses would be counteracted by use of the recommended overage, at least one food vehicle was able to increase vitamin D supply to ≥ 5 μg/d in all LMICs. Intakes approaching 5 μg/d have the ability to maintain serum 25(OH)D ≥ 25 nmol/L in ˜90% of individuals, even in the absence of UVB availability [33]. Achievement of such an intake by food fortification, even as a step towards ultimately attaining the higher recommended intake of 10 μg/d [32], would drive real-world progress in terms of tacking vitamin D deficiency.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.jsbmb.2019.105479.

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