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Iron Fortification through Universal Distribution of Double-Fortified Salt Can Increase Wages and Be Cost-Effective: An Ex-Ante Modeling Study in India

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ABSTRACT

Background: The alleviation of iron deficiency through iron supplementation has not effectively reduced anemia in India, mainly due to low compliance. Food fortification with iron is considered a viable alternative, and the provision of double-fortified salt (DFS; with iron and iodine) has been mandated in public health programs. Limited evidence exists on its benefit–cost ratio.

Objective: In this study we sought to estimate the economic benefit in terms of increased wages in relation to introduction of DFS in reduction of anemia and the cost of doing so.

Methods: The economic benefit of introducing DFS in India was derived using a series of mathematical, statistical, and econometric models using data from national surveys capturing earnings and dietary iron intake of the population. Anemia status was predicted from data on dietary intake, sanitation, and for women, menstrual losses. The impact of iron deficiency anemia (IDA) on wages was estimated using a Heckman Selection model and 2-stage least squares procedure. Benefit of DFS was estimated through increased wages attributed to anemia reduction compared with its cost.

Results: Men and women with IDA had lower wages (by 25.9%, 95% CI: 11.3, 38.1; and by 3.9%, 95% CI: 0.0, 7.7, respectively) than those without IDA. Additional iron intake through DFS was predicted to reduce prevalence of IDA (from 10.6% to 0.7% in men and 23.8% to 20.9% in women). The economic benefit–cost ratio of introducing DFS at a national level was estimated to be 4.2:1.

Conclusions: Iron fortification delivered through DFS under a universal program can improve wages and be sufficiently cost-effective for its implementation at scale in India. *J Nutr* 2022;152:597–611.

Keywords: Anemia, iron deficiency anemia, double-fortified salt, economics of iron fortification, benefit–cost ratio

Introduction

Anemia affects 27% of the population globally and 89% of the population in developing countries (1). In India, anemia continues to be a public health problem despite years of policy efforts, with >50% prevalence reported in women aged 15–49 y and children aged 6–59 mo, and a moderate prevalence of 23% reported in men as well, showing a decrease of about 2% in women and 1% in men from the previous survey a decade back (2). About 50% of anemia worldwide is thought to be due to iron deficiency (3). Iron deficiency is particularly of concern because beyond decreasing the oxygen carrying capacity of the blood, which leads to increased weakness and fatigue, it affects many metabolic pathways and other downstream functions (4). Consequently, by causing reduced productivity and work capacity in adults, iron deficiency anemia (IDA) affects wages and earnings (5). Horton and Ross (6) used data from 10 developing countries and showed that IDA contributes to ∼2–8% of losses in terms of gross domestic product (GDP), with estimated GDP losses at 6% for India. The Global Burden of Diseases Study of 2016 ranked IDA to be one of the leading causes of "years lived with disability" (7). IDA accounted for 3.5% of the total burden of disease as measured by disability-adjusted life years in India (8).

Anemia has a complex etiology and is not solely caused by the inadequate dietary intake of iron, as not all those considered anemic present with iron deficiency. Other nutrients can inhibit or enhance the absorption of dietary iron, but increased iron

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losses due to intestinal parasites are also important (9–13). Whereas supplementation or fortification can result in increased iron intake, diversity in diets may improve iron bioavailability by increasing the intake of enhancers of absorption like vitamin C or reducing the intakes of inhibitors like phytate (14, 15). Furthermore, nutritional deficiencies in vitamins such as vitamin A, riboflavin (B_2), pyridoxine (B_6), folate (B_9), cobalamin (B_{12}), D, and E, and minerals such as copper and zinc also contribute to anemia by affecting absorption and immune response (16). Thus, addressing diet diversity along with iron fortification is critical in countries like India, where poor-quality diets are common (17). Poor sanitation and hygiene practices (18) are also important since chronic inflammation reduces iron absorption and intestinal parasites increase iron losses.

The program of weekly iron and folic acid supplementation (WIFAS) recommended by the WHO (19), though adopted for use in India (20), has had limited success due to poor implementation and compliance (21). An alternate solution is food fortification, which requires no behavioral modification. Although a few fortified staple foods can successfully reach large sections of the population, there is a risk of overconsumption with cereal fortification, given that cereal consumption by certain sections of the population is high in India with lots of variation in consumption by wealth status and region, and fortified foods are thus likely to lead to adverse health risks with risk of excess iron intake (22–25). Salt is one such fortified staple (26), with a per capita intake of about 8 g/d in India (27) across all income groups. The iodization of salt has been well established in India (2) and offers the infrastructure to include additional nutrients like iron. In this context, technology for the production of double-fortified salt (DFS) with iron and iodine has been developed and tested in India at scale (28), adding about 25% of the cost to the producer of iodized salt currently available. In absolute terms, the cost differential is roughly 16–17 US cents/(person/y) or 12 Indian rupees (INR)/(person/y) (28). Well-allocated subsidies may further reduce incremental costs. With the already high coverage of iodized salt in India (93%) (2), introduction of DFS through social safety net programs and open markets is achievable. Currently, DFS is being introduced through social safety net programs such as the Public Distribution System (PDS), Mid-day Meal Scheme (MDM), and Integrated Child Development Services (ICDS) by a few state governments in India either free or at a subsidized price (29).

As a preliminary step, a formal benefit–cost analysis is required before scaling up DFS nationally. The objective of the present study was to understand the economic implications of DFS through a benefit–cost analysis by evaluating the potential benefit of DFS consumption on IDA reduction and the enhancement of adult wages. Statistical, mathematical, and econometric techniques were used for simulating IDA and its association with adult wages.

Materials and Methods

Sources of data

Nationally representative survey data were used for analysis. The primary data source was the 68th Round (2011–2012) unit-level data obtained during the Consumer Expenditure Survey (27) and the Employment–Unemployment Survey (30) collected by the National Sample Survey Office (NSSO). The former was used for calculating nutrient intake estimates, whereas the latter provided information on employment and wages (in INR). The national prevalence of anemia was obtained from the National Family Health Survey 2015–2016 (NFHS-4) (2). The WHO's cutoff for anemia was used, 12 g/dL hemoglobin (Hb) for women and 13 g/dL for men (31). For validation of our modeling, an external unpublished primary data set was used (details provided later). The detailed information on the data sets used is available in **Supplemental Method 1**. **Figure 1** shows the conceptual framework of this modeling exercise and the data sources used at different stages.

Statistical matching and triangulation of data

In the absence of a single data set on dietary iron intake and wages, we first created a synthetic nationally representative data set with both nutrient intake and earnings of adult men and women. Thus, the NSSO Consumer Expenditure Survey (27) and the Employment–Unemployment Survey (30) were triangulated (by statistically matching unit-level data). The fundamental principle of this statistical matching technique was to identify a set of common variables between the data sets that explain the variation of both the outcome and exposure (32). The employment–unemployment data, which contained information on earnings and occupation, were chosen as the recipient data set, and the consumer expenditure data were chosen as the donor data set (Figure 1). The common variables that were used for matching the 2 data sets were household size; household type, which was based on whether the subject's employment status was classified as regular salaried, casual, or self-employment in agriculture or non-agriculture in rural or urban area; religion; social group by caste; total value of land possessed (hectares); per capita monthly expenditure (INR, 1 USD = 74.18 INR); age; sex; marital status; and education. Individual level data on employment and wages in the employment–unemployment survey were matched to individual level daily dietary intake in terms of per consumer unit (PCU) (based on energy requirement of a woman expressed in relation to that of a reference man) (33, 34). The nutrient intakes of iron, calcium, phytate, polyphenol, and ascorbic acid [all in mg/(consumer unit/d)] and intake of salt, meat, and egg [all in g/(consumer unit/d)] were computed. Descriptions of both surveys are given in Supplemental Method 1.

To perform statistical matching (32) a nonparametric technique, the "nearest neighbor distance hot deck method" was employed (**Supplemental Figure 1**). The final synthesized matched data set consisted of wages and food/nutrient intakes of 126,671 and 124,515 adult men and women, respectively, aged 15–49 y. The triangulation was validated by examining the correlation between household expenditures from both the surveys and comparing the regression coefficients of per

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Supplemental Methods 1–4, Supplemental Figure 1, and Supplemental Tables 1 and 2 are available from the "Supplementary data" link in the online posting of the article and from the same link in the online table of contents at https://academic.oup.com/jn/.

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Abbreviations used: BCR, benefit–cost ratio; DFS, double-fortified salt; GDP, gross domestic product; Hb, hemoglobin; ICDS, Integrated Child Development Services; IDA, iron deficiency anemia; IMR, inverse Mills ratio; INR, Indian rupees; IV, instrumental variable; MDM, Mid-day Meal Scheme; MT, metric ton; NFHS, National Family Health Survey; NSSO, National Sample Survey Office; OLS, ordinary least square; PCU, per consumer unit; PDS, Public Distribution System; USD, United States Dollar; WRA, women of reproductive age; 2SLS, 2-stage least square.

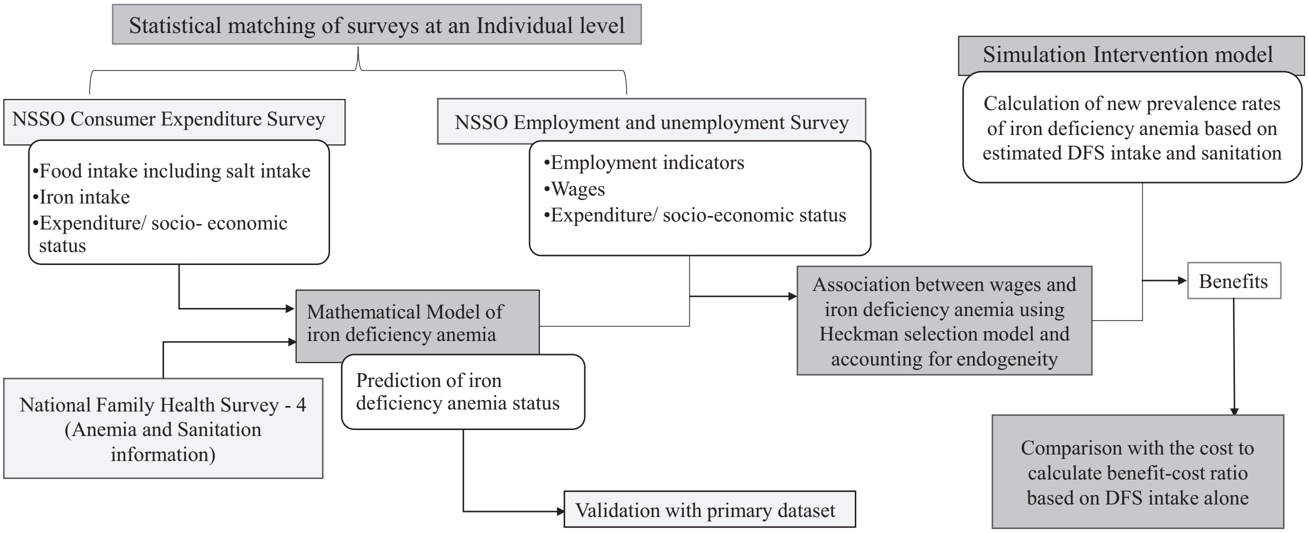

FIGURE 1 Analysis framework flow chart depicting various methods and data sets adopted for the study. Dark-gray boxes indicate the main analysis which is statistical matching, mathematical, and simulation modeling, and econometric and benefit–cost models. Light-gray boxes describe the corresponding data used. DFS, double-fortified salt; NSSO, National Sample Survey Office.

capita expenditures in matching variables in the 2 data sets (**Supplemental Method 2**). Records with unmatched and missing data on any variable considered in the analysis were dropped from the analysis. Thus 4727 and 4368 records for men and women, respectively, were excluded from analysis.

Mathematical model to predict the prevalence of IDA and simulation for reduction in IDA

The impact of DFS on wages was expected to be mediated through IDA. To obtain an estimate of the prevalence of IDA, mathematical modeling based on Thankachan et al. (35) using the dietary iron intake in the triangulated data set was performed for both men and women. This prediction considered the regulation of iron absorption while modeling the effect of iron supplementation on Hb status (g/dL concentration). To obtain the relation between Hb status and regulation of fractional absorption, estimates of iron absorption had to be adjusted for dietary factors that either enhance or inhibit iron absorption (36, 37) (**Supplemental Method 3: Equations *S1*–*S12***).

In both men and women, the model considered 2 body iron storage pools, “Hb” and “other storage,” with daily loss of iron at a constant rate from the other storage pool. In women, an additional factor for menstrual iron loss from the Hb pool was added. The model also assumed that fractional absorption of iron was upregulated when Hb status was poor (35). To arrive at the prevalence of IDA in men and women, an algorithm was used as described in Supplemental Method 3 (**Equations *S13–S15***). Additionally, environmental factors, particularly inadequate access to sanitation facilities that interfere with iron absorption (38, 39), were also considered in the model. Access to sanitation facilities was estimated by comparing the quintile income ranking of the subject with the percentage of the population with access to sanitation in that particular district based on NFHS-4 (2). For example, if the subject was in the second-poorest quintile income group, and <60% of the population had access to sanitation facilities in that district, they were classified as unable to access sanitation facilities. Access to sanitation was defined as use of nonshared toilets that are flush/pour flush toilets to piped sewer systems, septic tanks, and pit latrines; ventilated improved pit/biogas latrines; pit latrines with slabs; and twin pit/composting toilets (2). Further, the proxy-Hb concentrations of subjects who were classified as unable to access sanitation facilities were dropped by 0.98 g/dL based on age and place of residence (urban/rural) adjusted regression coefficient of poor sanitation in NFHS-4 data (2).

A sensitivity analysis was conducted on the model, where all nutrient inputs except iron were systematically increased and decreased by 10%, and estimated IDA prevalence in the population with these variations was compared with the original estimate. The same algorithm was used to predict IDA prevalence and was validated against prevalence obtained using measured Hb and serum ferritin concentrations from primary data on dietary intake and level of Hb and ferritin in a sample of 374 nonpregnant women from Jharkhand state in India. This study was conducted as a baseline survey to study the impact of the rollout of DFS on anemia. However, the rollout of DFS through the PDS did not materialize.

The model then simulated the expected change in IDA prevalence if DFS fortified with 1 mg iron/g salt was hypothetically consumed over a period of time at a national level (**Supplemental Method 4, Equations *S16*and*S17***). Specifically, simulation was run to the point where the change in prevalence rate of IDA was assumed to be zero. Additionally, simulation of DFS in the diet coupled with improved sanitation facilities was performed to investigate the effects on prevalence of IDA. However, when considering sanitation, the required time expected to be needed to observe the change in prevalence was not included.

Recovery from anemia in men and women was considered when the proxy-Hb concentration was below the normal threshold concentrations crossed the sex-specific threshold value (>12 g/dL for women and >13 g/dL for men) for normal Hb, after accounting for the DFS intervention. Percentage of recovery was obtained by simulation using the mathematical modeling.

Econometric and benefit–cost models

The expected changes in the prevalence of IDA simulated through the mathematical model was used for estimating the potential change in wages. Regression analysis was performed

TABLE 1 Variables used for calculating monetary benefits at the national level[1]

	Men	Women
β regression coefficient for IDA dummy	0.30	0.04
Change in wages,[2] %	35.0	4.1
Percentage points change in prevalence of IDA after 5 y,[3] %	6.1	3.0
Average daily wages, INR[4] (self-employed not included)[5]	250	174
Share of given employed group in total population,[6] %	10.1	2.9
Wage-earning adult population, *n*	120,840,000	35,160,000

[1] IDA, iron deficiency anemia; INR, Indian rupees; NSSO, National Sample Survey Office.

[2] Respective percentage change in wages was estimated using final-outcome model given in Equation *3* and the corresponding coefficients in Table 6, column 3 for men and Table 9, column 1 for women.

[3] Percentage change in prevalence of IDA after 5 y was predicted based on the mathematical model which indicates more than half of the reduction takes place within 5 y.

[4] INR 74.18 = USD \$1 as of 29 September 2021.

[5] Average wages for men and women were calculated from the NSSO's 68th Round of Employment–Unemployment Survey (2011–2012).

[6] Share of employed men and women in the total population was calculated from NSSO's 68th Round of Employment–Unemployment Survey (2011–2012). The total population multiplied by the percentage share of the given employed group in the population provides the estimate of the share of wage-earning adult population in India (Equation *4*).

to examine the impact of predicted IDA (mathematical model) on wages (triangulated data set). We used the Mincer Earnings Function (40), where log wage was regressed on IDA status along with other determinants. As an individual's choice of labor force participation depends on his/her reservation wage, running an ordinary least square (OLS) regression on wages would imply inclusion of only those individuals offered wages greater than their reservation wages, thus resulting in a nonrandom sample and violation of the Gauss–Markov assumption of random sampling (41). Reservation wage is a specific minimum wage at or above which the individual would be willing to participate in the labor market given availability of employment opportunities. To control for this selection bias in labor force participation, we used the Heckman Selection Model (41), which corrects for inherent biases by first estimating labor force participation through a probit model and subsequently inserting the inverse Mills ratio (IMR) calculated from the above model in the final outcome model [Mincers earnings equation (40, 42)]. The participation equation was estimated using a probit model, as follows:

$$\Pr\ (\ LFP_i = 1) = \Phi\ (\beta_1\ +\ \beta_2\, no\_dependentchildren_i \\ +\beta_3\, pc\_monthlyexp_i\ +\ \gamma \underline{Z}\ +\ \mu_i\Big) \qquad (1)$$

where the dependent variable is the probability of participating in the labor force (0, not employed; 1, employed) and employment status is based on an individual's report of being self-employed, regular salaried employed, or wage employed; Φ is the cumulative distribution function of the standard normal distribution, the number of dependent children <5 y of age, and the per capita monthly expenditure are the exclusion restrictions for the Heckman selection model; $\underline{Z}$ is the vector of independent variables that affect labor force participation, such as land owned (in hectares), marital status, education attainment level, age, and regional zones; and μ_i is the error term. The exclusion restriction in the participation equation addresses issues of multicollinearity in the outcome model. We modeled the participation equation separately for men and women.

Further, endogeneity can create a problem in the outcome model due to the presence of omitted variables that affect both earning capacity and health status. For example, unobserved individual and household characteristics may affect both these variables. Hence, the error term can become correlated with the outcome variable, violating the key assumption of OLS of uncorrelatedness, biasing the estimates (43). A 2-stage least square (2SLS) estimation procedure was performed to address endogeneity, where instrumental variables (IVs) were used to segregate the part of the endogenous variable that may be correlated with the error term (44). Specifically, IVs indirectly affect the dependent variable through its impact on the endogenous variable. Since the endogenous variable (IDA) was binary, we needed to be aware of performing forbidden 2SLS regression, first correcting for the nonlinear functional form, so that a linear equation could be run in the first stage, as is applicable in the 2SLS procedure (44). Specifically, we regressed the endogenous variable (whether an individual has IDA or not) on the instruments selected along with the explanatory variables as a probit model.

The probit equation is given as follows:

$$Pr\ (IDA_i = 1) = \alpha + \theta \underline{I} + \tau \underline{X} + \delta IMR_i + \epsilon_i \qquad (2)$$

Where $\underline{I}$ is a vector of IVs, i.e., price of rice and rice products; price of wheat flour and wheat products; price of milk and milk products; and price of eggs, fish, and meat; and $\underline{X}$ is a vector of other determinants of wages, such as land owned, marital status, education attainment level, age, regional zones, physical activity status, social group, and location of residence (urban/rural). Physical activity was categorized as sedentary, moderate, and heavy based on the occupation engaged in. The Inverse Mills Ratio (IMR) from the participation model, which is the ratio of the probability density function over the cumulative distribution function of the distribution from the participation equation, was used as an additional regressor to control for the sample selection bias, and ϵ_i is the error term. The economic rationale behind using prices as IVs was that prices are outside the control of the household and are determined at a market level, hence they are expected to be uncorrelated with the outcome variable (wages) but correlated with the endogenous variable (IDA) (45–47).

The predicted value from this model was regressed again on the endogenous variable, treating it as a linear probability model, the prediction of which was ultimately used in the final-outcome model. Various postestimation tests were conducted to check the strength and validity of the instruments. To check whether the endogenous regressor in a model is exogenous or not, Wooldridge's robust score test and a robust regression-based test were conducted (48). The strength of the instrument

TABLE 2 Household characteristics from triangulated data[1]

	Men	Women
Number of observations, *n*	126,671	124,515
Age, y	29 [21, 38]	30 [22, 38]
Household size, *n*	5 [4, 6]	5 [4, 6]
Land possessed, hectares	0.03 [0.01, 0.63]	0.03 [0.01, 0.62]
Per capita monthly expenditure (INR/mo)[2]	1210 [853, 1840]	1180 [842, 1800]
Religion, %		
Hinduism	81.9	81.4
Islam	13.2	13.6
Christianity	2.0	2.2
Other	2.9	2.8
Social group, %		
Schedule tribe	8.5	8.6
Schedule caste	18.9	18.8
Other backward class	43.4	43.7
General	29.2	29.0
Household type, %		
Agriculture	39.2	39.6
Nonagriculture	60.8	60.4
Married, %	60.6	74.3
Education, %		
Illiterate	15.5	31.6
Below primary education	8.7	9.1
Above primary education	75.8	59.3
Iron intake, mg/(consumer unit/d)	13.8 [10.2, 17.7]	11.2 [8.23, 14.3]
Vitamin C intake, mg/(consumer unit/d)	46.8 [33.9, 64.2]	38.0 [27.5, 52.5]
Calcium intake, mg/(consumer unit/d)	374 [257, 528]	302 [208, 431]
Polyphenol intake, mg/(consumer unit/d)	146 [113, 190]	118 [91.7, 156]
Phytate intake, mg/(consumer unit/d)	1750 [1360, 2210]	1410 [1100, 1790]
Salt intake, g/(consumer unit/d)	8.8 [7.0, 11.8]	7.5 [5.91, 9.96]
Egg intake, g/(consumer unit/d)	0 [0, 5]	0 [0, 4]
Fish and meat intake, g/(consumer unit/d)	7.95 [0, 19.9]	6.88 [0, 16.9]

[1] Values are median [quartile 1, quartile 3]. INR, Indian rupee; USD, United States Dollar.

[2] INR 74.18 = USD $1 as on 29 September 2021.

was tested based on the first-stage regression statistics, where the F-statistic for IVs should exceed the value of 10 for reliable statistical inference (49).

The final outcome model included the predicted value of the endogenous variable, IMR, along with the other exogenous variables. The final-outcome model is given as follows:

$$log\ wages_i = \alpha + \beta\widehat{IDA}_i + \gamma\underline{X} + \delta IMR_i + \varepsilon_i, \qquad (3)$$

where the dependent variable is the log of wages calculated as average daily earnings (in INR), $\widehat{IDA}$ is the predicted value of IDA from abovementioned linear probability model, $\underline{X}$ is a vector of other determinants of wages as described above, and ε is the error term. The error terms in the selection and outcome model (μ and ε, respectively) are distributed as: $\varepsilon,\ \mu \sim N(0, 0, \sigma_\varepsilon^2,\ \sigma_\mu^2,\ \rho_{\varepsilon\mu})$, i.e., the error terms are normally distributed with mean 0 and variances as indicated above, and these correlate with each other. The error terms are also assumed to be independent of both sets of explanatory variables. Note that if there is no endogeneity problem then Equation *3* would be directly used after Equation *1* with direct estimates of IDA from the mathematical model.

Finally, a benefit–cost analysis of introducing DFS (an additional 1 mg iron/g salt consumed) at the national level was performed. Benefits were computed as increase in wages due to a shift of a section of the population from IDA to non-IDA status. As described earlier, this proportion was estimated using

TABLE 3 Prevalence of IDA: status quo and post different types of intervention through mathematical modeling using the triangulated data set[1]

	Modeled prevalence of IDA (status quo)[2]	Modeled prevalence after DFS intervention[3]	Modeled prevalence after sanitation intervention[4]	Modeled prevalence after both DFS and sanitation intervention[5]
Men	10.6%	0.7%	3.7%	0.1%
Women	23.8%	20.9%	14.6%	3.6%

[1] DFS, double fortified salt; IDA, iron deficiency anemia.

[2] Modeled prevalence rate of IDA without any intervention.

[3] Modeled prevalence rate of IDA if DFS fortified with 1 mg iron/g salt consumed.

[4] Modeled prevalence rate of IDA if improved access to sanitation was introduced.

[5] Modeled prevalence rate of IDA if both DFS fortified with 1mg iron/g salt and improved access to sanitation were introduced.

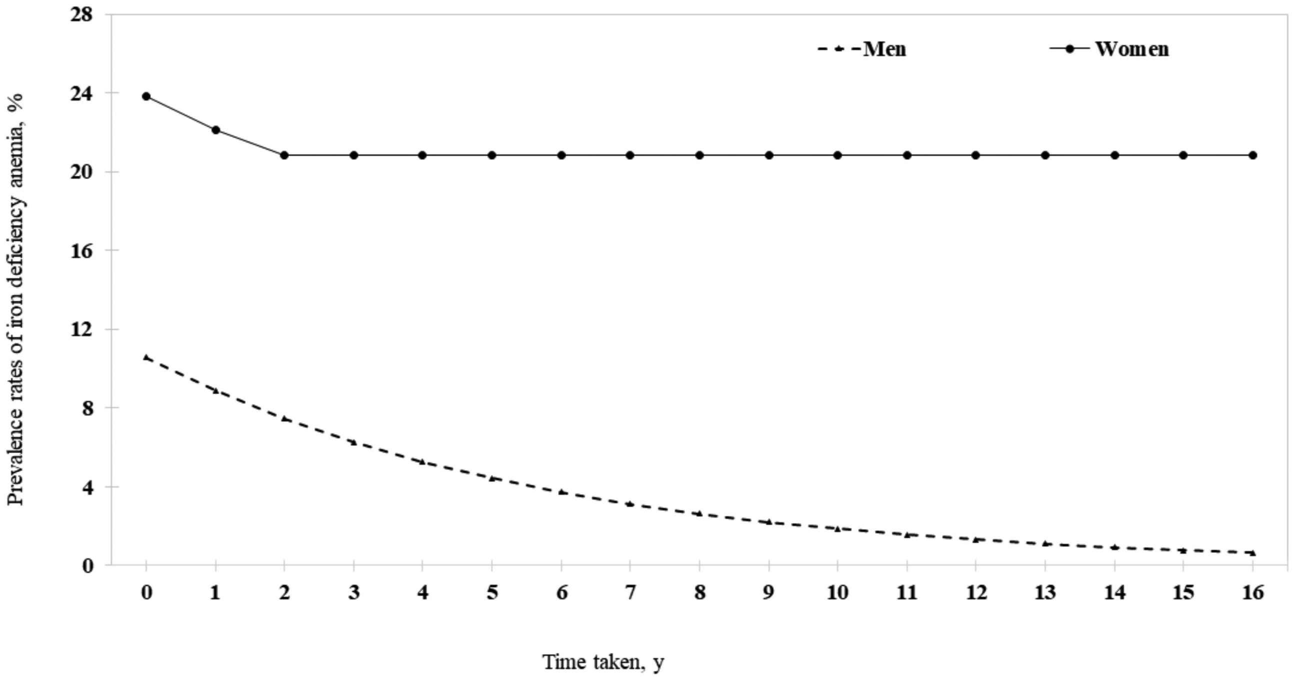

FIGURE 2 Expected change in prevalence rates of IDA over time for men (n = 126,671) and women (n = 124,515) estimated using the mathematical model if DFS fortified with 1 mg iron/g salt was hypothetically consumed until the time point where the expected change in prevalence of IDA is zero. DFS, double-fortified salt; IDA, iron deficiency anemia.

the mathematical model. The percentage equivalent of the IDA coefficient from the final outcome model was used to calculate the expected change in wages, assuming that wages of the IDA population would change by estimated difference in wages between the IDA and non-IDA population. The calculation for monetary benefits is given by Equation 4:

$$\begin{aligned}&Average\ daily\ wages\,(INR) + Expected\ change\ in\ wages\ (\%)\\&\quad + Change\ in\ prevalence\ rate\ of\ IDA\ (\%)\\&\quad + Share\ of\ given\ employed\ population\ group\ in\ total\\&\quad population\ (\%) + Total\ population\ of\ India\ +\ 365 \qquad (4)\end{aligned}$$

The variables used are listed in Table 1. These benefits were aggregated for all of the employed population groups, both men and women, to get the monetary benefits at the national level for the given time period. This population group specifically included the regular salaried employees and casual laborers.

The estimated benefits from Equation 4 were compared with the cost of DFS. The cost included fortification cost (iron premix), marketing, and operational costs, but excluded the cost of iodized salt. This exclusion was applied because the benefits considered here pertain only to the additional consumption of iron in the salt and iodized salt is already available through a universal program in India and is widely consumed. The monetary benefits for self-employed workers, constituting ∼20% of the population, could not be calculated due to unavailability of data on their earnings. Therefore, they were excluded from the analysis. The benefit–cost ratio (BCR) may be higher if earnings of self-employed workers increase due to recovery from IDA. The BCR was calculated for a period of 5 y, which was considered a reasonable period for significant reductions in IDA prevalence. The BCR for each year for the next 5 y was calculated. To arrive at the cumulative BCR over 5 y, all the values estimated from individual years for both men and women were summed. Future benefits and costs were discounted by a 3% discount rate to their present value on the premise that a rupee today is worth more than in later years (50). All modeling was performed separately for men and women, and analyses were done using R version 3.4.1, Stata version 14, and Python 3.

Results

Data description

Table 2 shows data characterizing the sociodemographic profiles and nutrient and food intakes of men and women in the final matched or triangulated data set. The median ages were 29 y (IQR: 21–38 y) and 30 y (IQR: 22–38 y) and their median per capita monthly expenditures were INR 1200 (IQR: 853–1841) and INR 1180 (IQR: 842–1800), respectively. The PCU daily intakes for men and women, respectively, were 13.8 mg (IQR: 10.2–17.7 mg) and 11.1mg (IQR: 8.2–14.3 mg) for iron, whereas intakes for men and women of iron absorption inhibitors, such as polyphenols, were 146 mg (IQR: 113–190 mg) and 118.4 mg (IQR: 91.6–156 mg), and phytate were 1750 mg (IQR: 1360–2210 mg) and 1410 mg (IQR: 1100–1790 mg). Median daily salt intakes were 8.8 g (IQR: 7.0–11.8 g) and 7.5 g (IQR: 5.9–10.0 g) for men and women, respectively.

Statistical matching and triangulation of data

Within the triangulated data, the correlation coefficient between individual expenditures from the consumer expenditure survey, and the employment–unemployment survey was high ($r = 0.76$ in men and $r = 0.70$ in women). Since both surveys had data on per capita expenditure, it was assumed that if the data sets matched, the per capita expenditures in both data sets would be comparable and therefore when regressed against the matching variables in the employment–unemployment data would give

TABLE 4 Labor force participation model: men[1]

Dependent variable: employment status (whether an individual is employed or not)	Labor force participation model (coefficients)	95% CI
Land owned, hectares	-1.92×10^{-6}	-1.18×10^{-5}, 7.94×10^{-6}
Marital status: not married[2]		
Married	0.83	0.77, 0.89
Education status: illiterate[2]		
Literate without formal or below primary education	0.38	0.24, 0.52
Primary education or above	− 0.28	−0.36, −0.19
Dependent children <5 y old, *n*	0.16	0.13, 0.19
Per capita expenditure, INR/mo[3]	-5.74×10^{-5}	-7.01×10^{-5}, -4.46×10^{-5}
Age, y	0.07	0.07, 0.08
Regional zones of India[4]: North[2] *		
West	0.06	0.01, 0.12
Central	0.03	−0.05, 0.11
East	− 0.002	−0.06, 0.06
South	0.04	−0.02, 0.10
Northeast	0.05	−0.02, 0.11
Constant	− 1.34	−1.46, −1.22
Number of observations, *n*	111,512	
Pseudo R-square	0.39	

[1] Coefficient estimates and 95% CIs are from the probit model labor force participation equation (Equation *1*). The choice to participate in the labor market for men was estimated using the labor force participation equation i.e., whether a man is employed or not (binary variable) by adjusting the socioeconomic demographics factors (land owned, marital status, education, dependent children <5 y old, per capita expenditure, age, and regional zones of India). INR, Indian Rupee; USD, United States Dollar.

[2] Reference variable.

[3] INR 74.18 = USD $1 as on 29 September 2021.

[4] Regional zones of India: North: Jammu, Kashmir, Himachal Pradesh, Punjab, Chandigarh, Uttarakhand, Haryana, Delhi, and Uttar Pradesh; West: Rajasthan, Gujarat, Daman, Diu, Dadar, Nagar Haveli, Maharashtra and Goa; Central: Chhatisgarh, Madhya Pradesh; East: Bihar, West Bengal, Jharkhand and Odisha; South: Andhra Pradesh, Karnataka, Lakshadweep, Kerala, Tamil Nadu, Pondicherry, and Andaman and Nicobar Islands; Northeast: Sikkim, Arunachal Pradesh, Nagaland, Manipur, Mizoram, Tripura, Meghalaya, and Assam.

similar estimates. Thus, the log per capita expenditure of men and women from both the data sets regressed on matching variables from employment–unemployment data gave model fit statistics that were comparable. The R^2 values of the models were 38% compared with 40% for men (**Supplemental Table 1**) and 37% compared with 38% for women (**Supplemental Table 2**) and yielded comparable estimates, thus validating the triangulation and indicating a reasonable and comparable proportion of variation explained in the per capita expenditure by the matching variables in both data sets.

Mathematical model to predict the prevalence of IDA and simulation of reduction in IDA

The calculated prevalences of IDA from the mathematical model were 10.6% and 23.8% in comparison with the estimated values of 11.4% and 26.6% for men and women, respectively, in the NFHS-4 survey (**Table 3**). The prevalence of IDA based on NFHS-4 was calculated as 50% (attributable to iron deficiency) of the total anemia prevalence (3) in men (22.7%) and women (53.1%). The estimated change in IDA prevalence, due to either introduction of DFS alone or improvement in sanitation alone, or both together, was from 10.6% to 0.7%, 3.7%, or 0.1% in men (Table 3) respectively. In women, the corresponding change was from 23.8% to 20.9%, 14.6%, or 3.6% (Table 3) respectively. With the drop of IDA from 10.6% to 0.7% in men and 23.8% to 20.9% in women after DFS intervention, we determined that by DFS intervention alone, 93% of men with anemia were expected to recover. On the other hand, only 12% of women with anemia were expected to become nonanemic.

When modeling time of recovery from IDA only through DFS intervention, the predicted period for recovery was 16 y in men, commensurate with the size of the population expected to recover (**Figure 2**). In women, the time period for attainable recovery was just under 2 y, and this shorter time of recovery was expected in women because a smaller proportion were expected to recover. Due to the long recovery period estimated for men, changes in IDA prevalence for the population were computed for specific time intervals (Figure 2). With 5 y of DFS intervention alone, in men, IDA prevalence could be reduced to 4.4%, whereas in women, the minimum attainable prevalence was 20.9% (Figure 2). The period of 5 y was chosen as the recovery time as more than half the change occurred within that period of time.

A sensitivity analysis of the mathematical model used to evaluate outputs when the noniron dietary inputs were increased and decreased by 10% showed no change in IDA prevalence for both men and women. As an additional validation, when the model was applied to a sample population from primary data on women from Jharkhand compared with actual measurement, the model predicted similar IDA prevalence. The model had a sensitivity of 85% and a specificity of 87% in classifying IDA.

Econometric and benefit–cost models

Outcome models were estimated separately for men and women (**Tables 4–6** and **Tables 7–9**). The final model selection was based on the significance for sample selection and endogeneity. The significance of the coefficient of the IMR in the outcome equation for men in Table 6 indicated that we fail to reject the null hypothesis of no evidence of sample selection bias, which indicates that the hypothesis that error terms of the participation and outcome models were not correlated was to be rejected. On the contrary, we rejected the null hypothesis for women and hence find evidence for sample selection bias (Table 9). We tested for endogeneity in the model for men

TABLE 5 Probit model for IDA on instruments: men

Dependent variable: whether an individual has IDA or not	Probit model for IDA on instruments (Coefficients)[1]	95% CI
Physical activity status: engaged in sedentary work[2]		
Moderate or heavy work	0.19	0.14, 0.23
Education status: illiterate[2]		
Literate without formal or below primary education	− 0.02	−0.11, 0.07
Primary education or above	− 0.15	−0.21, −0.08
Age, y	-2.1×10^{-3}	-6.34×10^{-3}, -2.15×10^{-3}
Social group[3]: others[2]		
General category	− 0.30	−0.35, −0.24
Marital status: not married[2]		
Married	− 0.20	−0.30, −0.09
Location of residence: urban[2]		
Rural	0.02	−0.04, 0.07
Land owned, hectares	-7.7×10^{-5}	-9.64×10^{-5}, -5.75×10^{-5}
Inverse Mills ratio	− 0.02	−0.19, 0.15
Regional zones of India[4]: North[2]		
West	0.60	0.50, 0.71
Central	0.87	0.77, 0.97
East	0.89	0.80, 0.97
South	1.02	0.93, 1.11
Northeast	1.15	1.05, 1.25
Price of rice and rice products at district level,[5] INR/kg	− 0.07	−0.08, −0.06
Price of wheat flour and wheat products at district level,[5] INR/kg	0.04	0.04, 0.05
Price of milk and milk products at district level, [5] INR/kg	− 0.01	−0.01, 0.00
Price of egg, fish and meat at district level, [5] INR/kg	-7.7×10^{-4}	-1.7×10^{-3}, 1.4×10^{-4}
Constant	− 1.08	−1.36, −0.80
Number of observations, *n*	109,622	
Pseudo R^2	0.18	

[1] Coefficient estimates with 95% CI are from the probit model estimated from Equation *2*. Whether an individual has iron deficiency anemia or not was regressed on Inverse Mills Ratio, various sociodemographic factors (physical activity, education, age, social group, marital status, location of residence, land owned, and regional zones of India), and instruments (price of rice and rice products, wheat flour and wheat products, milk and milk products, and egg, fish, and meat) to address endogeneity. IDA, Iron deficiency anemia; INR, Indian Rupees; USD, United States Dollar.

[2] Reference variable.

[3] Social group: others include schedule tribe, schedule caste, and other backward classes.

[4] Regional zones of India: North: Jammu, Kashmir, Himachal Pradesh, Punjab, Chandigarh, Uttarakhand, Haryana, Delhi, and Uttar Pradesh; West: Rajasthan, Gujarat, Daman, Diu, Dadar, Nagar Haveli, Maharashtra, and Goa; Central: Chhatisgarh, Madhya Pradesh; East: Bihar, West Bengal, Jharkhand, and Odisha; South: Andhra Pradesh, Karnataka, Lakshadweep, Kerala, Tamil Nadu, Pondicherry, and Andaman and Nicobar Islands; Northeast: Sikkim, Arunachal Pradesh, Nagaland, Manipur, Mizoram, Tripura, Meghalaya, and Assam.

[5] INR 74.18 = USD $1 as of 29 September 2021.

and rejected the null hypothesis of exogeneity between IDA and wages since the robust chi-square score (14.54) and robust regression *F*-statistic (5.64) were both significant (P value ≤ 0.05). Further, the strength of the IV model showed that the *F*-statistic (152.086) exceeded the value of 10, indicating a strong instrument. Whereas for women, neither the robust chi-square score nor the robust regression *F*-statistic were significant (P value > 0.05), suggesting an exogenous relation between IDA and wages. Therefore, in men, endogeneity between IDA status and wages was observed with no evidence of sample selection bias (Tables 5 and Table 6, column 3), whereas the reverse was observed in women (Table 7 and Table 9, column 1). Hence, we used a 2SLS approach addressing endogeneity through instrument selection for men (Equations 2 and 3) and Heckman selection model correction for sample selection bias for women (Equations *1* and *3*).

The estimated IDA coefficient, the main parameter of interest, was −0.30 (95% CI: −0.48, −0.12, $P = 0.001$) for men, indicating an average difference of 25.9% (95% CI: 11.3, 38.1) in earnings of IDA compared with non-IDA men (Table 6, column 3). A similar trend, although of a lower magnitude (−0.04; 95% CI: −0.08, 0.01; $P = 0.095$) was observed in women, with a difference of 3.9% (95% CI: 0.0, 7.7) in earnings IDA compared with non-IDA women (Table 9, column 1). These differences were equivalent to non-IDA men and women earning 35% and 4.1% more than their anemic counterparts, respectively, as calculated from their respective coefficients (Table 1).

We calculated the benefits over a 5-y period, during which significant reductions in IDA rates were expected (Figure 2). For men, at the end of year 5, the estimated change in prevalence was 6.1 percentage points. For women, however, the estimated change was around 3 percentage points at the end of year 2, with the model predicting no subsequent changes. Most benefits, therefore, accrued in the male population. The final additional cost of iron premix in DFS was estimated to be INR 12 (USD $0.16 or 0.17)/person/y computed using the actual production and other costs (28). Therefore, the BCR, jointly calculated for both men and women, was 4.2:1 when cumulative benefits and costs were examined over 5 y (**Figure 3**).

TABLE 6 Final wage outcome model for men[1]

Dependent variable (log of wages, INR[2])	Coefficients (without addressing endogeneity)	95% CI	Coefficients (2SLS model addressing endogeneity)	95% CI
IDA[3]: no[4]				
Yes	− 0.09	−0.12, −0.06	− 0.30	−0.48, −0.12
Physical activity status: engaged in sedentary work[4]				
Moderate or heavy work	− 0.42	−0.45, −0.39	− 0.41	−0.44, −0.38
Education status: illiterate[4]				
Literate without formal or below primary education	0.06	0.02, 0.09	0.05	0.02, 0.09
Primary education or above	0.21	0.18, 0.23	0.20	0.18, 0.23
Age, y	0.01	0.01, 0.02	0.01	0.01, 0.02
Social group[5]: others[4]				
General Category	0.17	0.14, 0.20	0.16	0.13, 0.19
Marital status: not married[4]				
Married	0.11	0.06, 0.17	0.11	0.06, 0.17
Location of residence: urban[4]				
Rural	− 0.28	−0.30, −0.25	− 0.27	−0.30, −0.25
Land owned, hectares	3.9×10^{-5}	2.4×10^{-5}, 5.4×10^{-5}	3.8×10^{-5}	2.3×10^{-5}, 5.3×10^{-5}
Inverse Mills ratio	0.04	−0.07, 0.14	0.03	−0.07, 0.14
Regional zones of India[6]: North[4]				
West	− 0.05	−0.08, −0.02	− 0.04	−0.08, −0.01
Central	− 0.31	−0.35, −0.28	− 0.29	−0.33, −0.25
East	− 0.17	−0.21, −0.14	− 0.15	−0.19, −0.11
South	0.15	0.12, 0.18	0.20	0.15, 0.25
Northeast	0.04	0.00, 0.08	0.08	0.03, 0.13
Constant	5.00	4.88, 5.12	5.00	4.88, 5.13
Number of observations, *n*	37,899		37,580	
Adjusted R^2	0.33		0.32	

[1] Log linear model regressing wages on IDA adjusting for physical activity, education, age, social group, marital status, location of residence (urban/rural), land owned, Inverse Mills ratio, and regional zones of India (Equation *3*). BCR, benefit–cost ratio; IDA, iron deficiency anemia; INR, Indian rupees; USD, United States Dollar; 2SLS, 2-stage least square.

[2] INR 74.18 = USD $1 as on 29 September 2021.

[3] The IDA coefficient from column 3 indicates an average difference of 25.9% (95% CI: 11.3, 38.1) in earnings of IDA compared with non-IDA or 35% difference in earnings of non-IDA compared with IDA, which was used in final BCR calculations.

[4] Reference variable.

[5] Social group: others include schedule tribe, schedule caste, and other backward classes.

[6] Regional zones of India: North: Jammu, Kashmir, Himachal Pradesh, Punjab, Chandigarh, Uttarakhand, Haryana, Delhi, and Uttar Pradesh; West: Rajasthan, Gujarat, Daman, Diu, Dadar, Nagar Haveli, Maharashtra, and Goa; Central: Chhatisgarh, Madhya Pradesh; East: Bihar, West Bengal, Jharkhand, and Odisha; South: Andhra Pradesh, Karnataka, Lakshadweep, Kerala, Tamil Nadu, Pondicherry, and Andaman and Nicobar Islands; Northeast: Sikkim, Arunachal Pradesh, Nagaland, Manipur, Mizoram, Tripura, Meghalaya, and Assam.

Discussion

India has an ongoing supplementation program and currently iron fortification of salt has been mandated by the government (51, 52). It is known that there is an association between anemia and economic productivity (6, 53, 54), but very little evidence exists on the specific economic benefit of iron fortification through salt. To our knowledge, no study has specifically focused on the economic benefit of DFS for a large population. Utilizing data from Indian national surveys, we used statistical, mathematical, and econometric modeling in a framework examining the path from iron intake to IDA and economic productivity, in terms of wages among men and women in India, to model the benefit–cost of DFS implementation. We found that consumption of DFS was associated with a reduction in IDA prevalence which varied by sex and time (from 10.6% to 0.7% in men and 23.8% to 20.9% in women). A difference in wages of men and women with IDA of 25.9% and 3.9%, respectively, compared with those without IDA, suggested that changes with DFS consumption were more marked in men. At the national level, the estimated benefit of improved wages attributed to anemia reduction from DFS consumption was >4 times higher than its cost (BCR, 4.2:1). Of course, when estimating BCR, we assumed an optimistic scenario of a 100% country-wide consumer compliance rate for DFS, probably an unlikely scenario presently with technological challenges still persisting with DFS (29). Lower compliance will result in a lower BCR.

Meta-analysis of efficacy studies on food fortification and biofortification have shown mixed results on IDA and anemia reduction or change in iron status (55–57). In a meta-analysis by Keats et al. (58), large-scale food fortification with iron resulted in a 34% decline in prevalence of anemia in women of reproductive age (WRA), although this was largely seen in pregnant women. Studies on children and women alone were included in the meta-analysis. However, limited studies are available on the economics of food fortification and biofortification with iron. Our estimates are close to the BCR estimates derived earlier for DFS in India, which ranged from 2.4:1 to 5:1, depending on the population studied (adult men, women, and children) (26). Unlike our study, this earlier study used Hb concentration and calculated changes in anemia prevalence from efficacy trials on DFS conducted across countries, including India. In addition, country-level estimates of macroeconomic indicators, along with assumptions from

TABLE 7 Labor Force Participation Model: women

Dependent variable: employment status (whether an individual is employed or not)	Labor Force Participation Model (Coefficients)[1]	95% CI
Land owned, hectares	3.01×10^{-5}	2.14×10^{-5}, 3.88×10^{-5}
Marital status: not married[2]		
Married	− 0.09	−0.14, −0.05
Education status: illiterate[2]		
Literate without formal or below primary education	− 0.15	−0.21, −0.09
Primary education or above	− 0.37	−0.41, −0.33
Dependent children <5 y old, *n*	− 0.04	−0.06, −0.02
Per capita expenditure, INR/mo[3]	-4.72×10^{-5}	-6.10×10^{-5}, -3.35×10^{-5}
Age, y	0.02	0.02, 0.03
Regional zones of India[4]: North[2]		
West	0.41	0.36, 0.46
Central	0.22	0.16, 0.29
East	− 0.24	−0.29, −0.19
South	0.50	0.45, 0.54
Northeast	− 0.05	−0.11, 0.01
Constant	− 1.17	−1.24, 1.10
Number of observations, *n*	111,245	
Pseudo R-square	0.08	

[1] Coefficient estimates and 95% CI are from the probit model labor force participation equation (Equation *1*). The choice to participate in the labor market for women was estimated using the labor force participation equation i.e., whether a woman is employed or not (binary variable) by adjusting the socioeconomic demographics factors (land owned, marital status, education, dependent children <5 y old, per capita expenditure, age, and regional zones of India). INR, Indian rupees; USD, United States Dollar.

[2] Reference variable.

[3] INR 74.18 = USD $1 as on 29 September 2021.

[4] Regional zones of India: North: Jammu, Kashmir, Himachal Pradesh, Punjab, Chandigarh, Uttarakhand, Haryana, Delhi, and Uttar Pradesh; West: Rajasthan, Gujarat, Daman, Diu, Dadar, Nagar Haveli, Maharashtra, and Goa; Central: Chhatisgarh, Madhya Pradesh; East: Bihar, West Bengal, Jharkhand, and Odisha; South: Andhra Pradesh, Karnataka, Lakshadweep, Kerala, Tamil Nadu, Pondicherry, and Andaman and Nicobar islands; North East: Sikkim, Arunachal Pradesh, Nagaland, Manipur, Mizoram, Tripura, Meghalaya, and Assam.

earlier effectiveness studies of iron therapy on physical capacity and work productivity across countries, were used for all the calculations.

A study on iron-fortified wheat flour from 10 developing countries estimated a higher median BCR of 8.7:1 (26). Although with this evidence wheat flour might be considered a better alternative to salt, significant challenges to its deployment will occur in populations where wheat is not a staple or where central processing and fortification of wheat flour is a challenge (26). There has been 1 case study on iron fortified wheat flour in the state of Gujarat, India, where the total cost of fortification was calculated to be USD $0.645/metric ton (MT) by large chakki mills which supply the safety net programs, and USD $0.485/MT by roller mills. About 74% of the wheat was milled through small chakkis in the informal sector where fortification could not be done (59). The key finding of impact on anemia has not been studied except in controlled efficacy studies, in Bengaluru and Pune on children between 6 and 15 y of age, where sodium iron EDTA–fortified wheat flour worked on iron deficient children in whom IDA decreased from 18% to 9% (60). The fortificant in wheat flour was sodium iron EDTA, which is more resistant to being inhibited by phytate, in the admittedly high-phytate Indian diets that are present. But there are 2 key reasons why scale-up is difficult to achieve: *1*) that it is difficult to get any universal quality control when there are so many wheat mills with varying capacities (and social safety nets are given the freedom to purchase their supplies from local contractors) and *2*) the fortificant is expensive compared with those used for salt and rice. Apart from this investigation there are to our knowledge no other previous studies on the impact of anemia in India (61). Currently very few districts in a few states have implemented wheat flour fortification in any of the safety net programs (52). The biofortification of a single crop is deemed to be a more cost-effective approach than fortification and supplementation (50). However, the same challenges can occur here as with the chemical fortification of a single cereal food. Therefore, it is essential to consider regional variation in consumption across the country and income groups, in addition to potential natural variability in the concentration of iron and inhibitors like phytate in the grain from year to year. For the above reasons, in India DFS as a universal fortification vehicle may be a better option.

Iron status has been linked with labor productivity among adults, so economic consequences of iron deficiency can be estimated through work capacity and wages (5). Our findings on the causal impact of IDA on wages are similar to those of a randomized controlled trial on iron supplementation in Indonesia, where a greater impact of improved wages by 15% in men and 6% in women was reported (5). Worker productivity and activity significantly improved in Sri Lankan female tea plantation workers provided with iron supplements, compared with those provided with a placebo (53). A secondary study of households employed in agricultural labor in India investigated a model that improved iron intakes to achieve recommended levels could increase wages from 5.0% to 17.3% (62).

We found the BCR of DFS to be promising, although benefits in women were lower than those in men due to a lower decline in prevalence coupled with lower labor force participation. This lower reduction in anemia in women is not unexpected. It is probably because in menstruating women, dietary iron directly balances its losses from the body iron stores and indirectly

TABLE 8 Probit model for IDA on instruments: women

Dependent variable: whether an individual has IDA or not	Probit model for IDA on instruments (Coefficients)[1]	95% CI
Physical activity status: engaged in sedentary work[2]		
Moderate or heavy work	0.03	−0.01, 0.07
Education status: illiterate[2]		
Literate without formal or below primary education	0.06	−0.02, 0.14
Primary education or above	0.24	0.11, 0.37
Age, y	− 0.03	−0.03, −0.02
Social group[3]: others[2]		
General category	− 0.02	−0.06, 0.02
Marital status: not married[2]		
Married	0.13	0.07, 0.18
Location of residence: urban[2]		
Rural	− 0.02	−0.06, 0.02
Land owned, hectares	-9.75×10^{-5}	-1.16×10^{-4}, -7.95×10^{-5}
Inverse Mills ratio	− 1.16	−1.60, −0.72
Regional zones of India[4]: North[2]		
West	− 0.33	−0.47, −0.18
Central	− 0.36	−0.47, −0.25
East	0.86	0.77, 0.95
South	− 0.35	−0.52, −0.18
Northeast	1.36	1.29, 1.43
Price of rice and rice products at district level, INR/kg [5]	− 0.02	−0.02, −0.01
Price of wheat flour and wheat products at district level, INR/kg [5]	0.02	0.02, 0.03
Price of milk and milk products at district level, INR/kg [5]	-3.52×10^{-3}	-4.55×10^{-3}, -2.49×10^{-3}
Price of egg, fish, and meat at district level, INR/kg [5]	− 0.01	−0.01, −0.01
Constant	1.89	1.15, 2.64
Number of observations, *n*	109,795	
Pseudo R-square	0.11	

[1] Coefficient estimates with 95% CI are from the probit model estimated from Equation *2*. Whether an individual has iron deficiency anemia or not was regressed on Inverse Mills ratio, various sociodemographic factors (physical activity, education, age, social group, marital status, location of residence, land owned, and regional zones of India), and instruments (price of rice and rice products, wheat flour and wheat products, milk and milk products, and egg, fish, and meat) to address endogeneity. IDA, Iron deficiency anemia; INR, Indian rupees; USD, United States Dollar.

[2] Reference variable.

[3] Social group: Others include schedule tribe, schedule caste, and other backward classes.

[4] Regional zones of India: North: Jammu, Kashmir, Himachal Pradesh, Punjab, Chandigarh, Uttarakhand, Haryana, Delhi, and Uttar Pradesh; West: Rajasthan, Gujarat, Daman, Diu, Dadar, Nagar Haveli, Maharashtra, and Goa; Central: Chhatisgarh, Madhya Pradesh; East: Bihar, West Bengal, Jharkhand, and Odisha; South: Andhra Pradesh, Karnataka, Lakshadweep, Kerala, Tamil Nadu, Pondicherry, and Andaman and Nicobar Islands; North East: Sikkim, Arunachal Pradesh, Nagaland, Manipur, Mizoram, Tripura, Meghalaya, and Assam.

[5] INR 74.18 = USD $1 as on 29 September 2021.

compensates losses in the Hb pool. For better absorption of dietary iron, environment-based strategies that minimize parasite-based blood losses and infections need to be addressed. Furthermore, nutritional deficiencies in folate, vitamin B_{12}, and vitamin A are also of a concern for addressing the problem of anemia (63, 64). Our modeling of DFS introduction coupled with improved sanitation resulted in a significant decline in IDA prevalence from 23.8% to 3.6% in women, a finding consistent with another modeling study that examined the effect of iron supplementation programs on anemia in WRA (25). The strategies to address this component should focus on investing in infrastructure and proper awareness campaigns related to water, hygiene, and infectious diseases. However, calculating benefits accruing by improvements in sanitation is beyond the scope of the present modeling. Adding other nutrients as fortificants, such as folate and vitamin B_{12}, to DFS or other fortificant vehicles may prove beneficial, provided it is within the limits related to multiple layers of fortification.

In an effectiveness study of consumption of DFS in Bihar, Banerjee et al. (65) found ∼12% reduction in prevalence of anemia and a mean increase of 0.41 g/dL in Hb among adolescents 13–17 y of age, but not in adults. Another study found positive impacts on Hb concentrations and consequently an ∼9.3% reduction in prevalence of anemia among primary school children in India (66). A meta-analysis of efficacy and effectiveness studies on impact of DFS showed a significant increase in Hb and serum ferritin, whereas there was a reduction in prevalence of anemia and IDA (67).

In the absence of a single inclusive nationally representative data set having information on food intake, health status, and earnings, we triangulated national-level data sets of the NSSO on consumer expenditure and employment, providing information on nutrient intakes and wages, respectively. Hence, we had to make several assumptions. The mathematical model assumes that iron absorption was based on daily iron consumption and modulated by a matrix of other nutrients provided by diet and the iron status of the individual. Iron absorbed was divided across 2 compartments, 1 of which was the Hb compartment, which was distributed across a normative plasma volume based on gender. Iron was lost from the

TABLE 9 Final wage outcome model for women[1]

Dependent variable (log of wages, INR[2])	Coefficients (without addressing endogeneity)	95% CI	Coefficients (2SLS model addressing endogeneity)	95% CI
Iron deficiency anemia[3]: no[4]				
Yes	– 0.04	–0.08, 0.01	0.07	–0.19, 0.34
Physical activity status: engaged in sedentary work[4]				
Moderate or heavy work	– 0.47	–0.54, –0.39	– 0.47	–0.55, –0.40
Education status: illiterate[4]				
Literate without formal or below primary education	– 0.23	–0.32, –0.14	– 0.23	–0.33, –0.14
Primary education or above	– 0.64	–0.84, –0.44	– 0.64	–0.84, –0.44
Age, y	0.06	0.05, 0.07	0.06	0.05, 0.07
Social group[5]: others[4]				
General category	0.08	0.02, 0.14	0.08	0.02, 0.14
Marital status: not married[4]				
Married	– 0.11	–0.18, –0.05	– 0.12	–0.18, –0.05
Location of residence: urban[4]				
Rural	– 0.18	–0.24, –0.12	– 0.17	–0.23, –0.11
Land owned, hectares	5.8×10^{-5}	2.81×10^{-5}, 8.78×10^{-5}	6.02×10^{-5}	2.96×10^{-5}, 9.08×10^{-5}
Inverse Mills ratio	2.90	2.16, 3.63	2.91	2.14, 3.67
Regional zones[6]: North[4]				
West	0.78	0.55, 1.02	0.79	0.54, 1.03
Central	0.33	0.17, 0.49	0.33	0.17, 0.50
East	– 0.69	–0.84, –0.54	– 0.73	–0.93, –0.52
South	1.04	0.77, 1.31	1.03	0.76, 1.31
Northeast	0.11	0.00, 0.23	0.06	–0.12, 0.24
Constant	– 0.004	–1.28, 1.27	– 0.03	–1.38, 1.31
Number of observations, *n*	10,626		10,507	
Adjusted R^2	0.32		0.32	

[1] Log linear model regressing wages on IDA adjusting for physical activity, education, age, social group, marital status, location of residence (urban/rural), land owned, Inverse Mills Ratio, and regional zones of India (Equation *3*). BCR, benefit–cost ratio; IDA, iron deficiency anemia; INR, Indian rupees; USD, United States Dollar; 2SLS, 2-stage least square.

[2] INR 74.18 = USD $1 as on 29 September 2021.

[3] IDA coefficient from column 1 indicates an average difference of 3.9% (95% CI: 0.0, 7.7) in earnings of IDA compared with non-IDA or 4.1% difference in earnings of non-IDA compared with IDA, which was used in final BCR calculations.

[4] Reference variable.

[5] Social group: others include schedule tribe, schedule caste and other backward classes.

[6] Regional zones of India: North: Jammu, Kashmir, Himachal Pradesh, Punjab, Chandigarh, Uttarakhand, Haryana, Delhi, and Uttar Pradesh; West: Rajasthan, Gujarat, Daman, Diu, Dadar, Nagar Haveli, Maharashtra, and Goa; Central: Chhatisgarh, Madhya Pradesh; East: Bihar, West Bengal, Jharkhand, and Odisha; South: Andhra Pradesh, Karnataka, Lakshadweep, Kerala, Tamil Nadu, Pondicherry, and Andaman and Nicobar Islands; North East: Sikkim, Arunachal Pradesh, Nagaland, Manipur, Mizoram, Tripura, Meghalaya, and Assam.

non-Hb compartment at a constant rate. For women, an additional daily iron loss came from the Hb compartment. The absorption was modulated by the iron status of the individual and divided equally between the Hb and non-Hb compartments. In subjects who were classified as being unable to access proper sanitation facilities, the Hb concentration was decreased by an additional factor. Our assumption that 50% of anemia was attributed to iron deficiency (3) may not be a true assumption, as data from other low- and middle-income countries show (68). Since evidence about IDA from all states in India is not available, a 50% assumption was used in the modeling. If the prevalence is lower, then BCR may be lower than what we have estimated since lesser reduction in IDA would be expected. Further, the BCR calculated was chosen for a period of 5 y as more than half the change occurred within that period of time. The benefits themselves were based only on improvement in wages and did not include other benefits such as reduction in health expenditure, reduction in maternal mortality, and overall improvement in wellbeing. If these benefits were included, BCR would be higher.

There are limitations of the present analysis. Due to data unavailability, benefits and costs accruing to the self-employed were not calculated. Furthermore, in the mathematical model, folate and vitamin B$_{12}$ (nutrients affecting red blood cell production) have not been considered. Sanitation and body iron loss were taken as a constant even though losses may vary. The model also assumed a constant volume of iron distribution in the body, as there are no data available to determine the blood volume of individuals. Based on the model, it is expected that individuals with high body blood volume require slightly more iron than those with lower volume owing to the higher volume of distribution of iron. Weight can be used as a proxy, but weight was not available in the NSSO data set. Because of these reasons, the mathematical model was limited to assessing whether or not subjects had IDA rather than considering the change in an individual's Hb content.

Although the success of the fortification depends on compliance by industry, level of population coverage, and quantity of consumption of salt by the consumer, we did not impute this data in the calculation of BCR as we do not have reliable figures of these at that time. A further limitation is that government costs for monitoring were not included in the econometric modeling as it is currently not available. Field test kits which have not been validated at scale have been

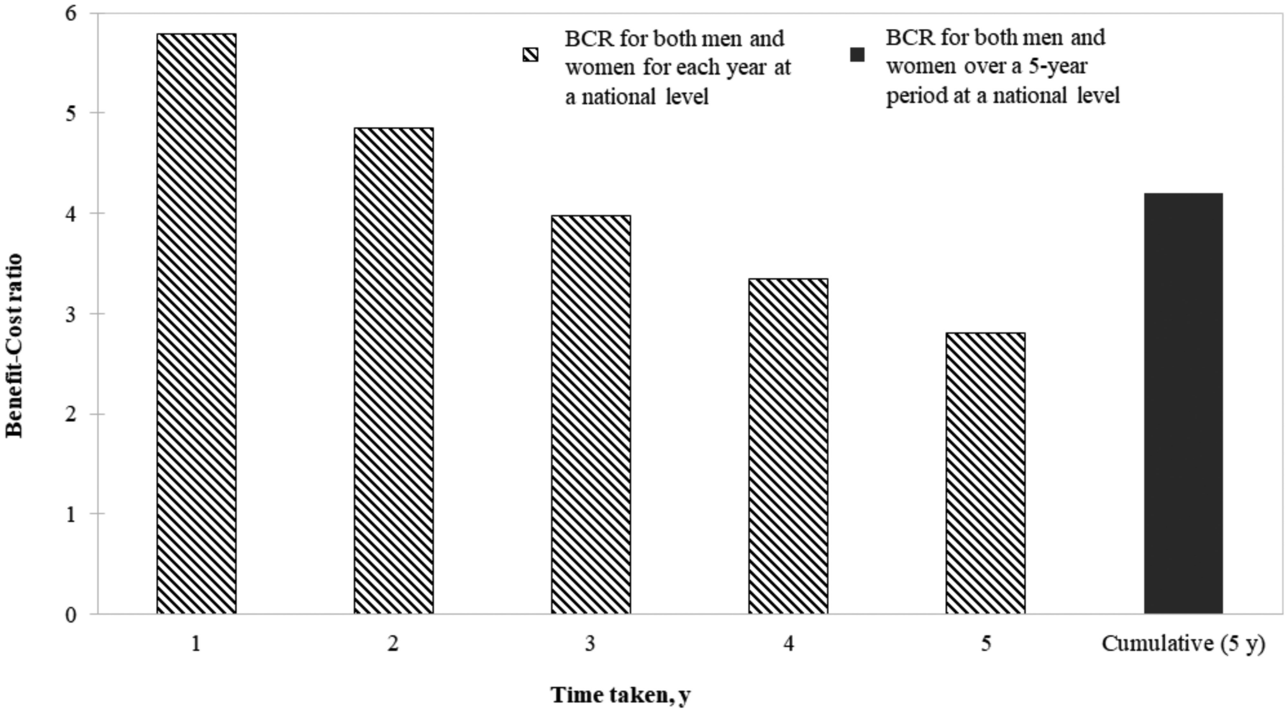

FIGURE 3 BCR for a 5-y period estimated using the econometric and benefit–cost model. Benefits were computed as expected change in wages if there is a shift in a section of the population from IDA to non-IDA status. BCR, benefit–cost ratio; DFS, double fortified salt; IDA, iron deficiency anemia.

developed to indicate the presence of iron in DFS qualitatively. For the present, monitoring of DFS quality needs to be done through testing of samples drawn in the field in accredited laboratories. The cost of a monitoring protocol to perform this function has therefore not been included in the cost estimates.

Our findings have important policy implications for scaling DFS at a national level. To achieve the WHO global target of 50% reduction in anemia in WRA by 2030 (69, 70), a multidimensional approach encompassing improved sanitation facilities along with fortification strategies to expedite benefits need to be considered by policymakers. Since the etiology of anemia is complex, other factors, such as improved dietary and agricultural diversity, food security, deworming, malaria control programs, etc., also need greater attention. For scale-up of DFS, both demand and supply-side policies must be considered. Demand-side policies, either of the central or state government, focusing on providing subsidies through safety net programs such PDS, ICDS, and MDM, and investment in behavior change communication related to consumer awareness about the nutritional value of the product and acceptance about DFS related to a perception of changing food color, should be prioritized (28). To achieve market equilibrium, supply should meet the demand so that economies of scale and adequate benefits are realized for all the stakeholders involved. Therefore, for effective implementation, supply-side factors such as smooth and sufficient supply of premix and efficient distribution should be addressed (28), in addition to certain other factors that need to be considered for effective roll out of DFS through public programs and open market.

At this early stage in the evolution of DFS, producers are not yet in a position to generate reasonable profits through DFS operations given the poor and inconsistent offtake both by public programs and underdeveloped open markets. These uncertainties result in unpredictable returns on investment and depress business incentives for private producers to invest in DFS production and product promotion (29, 71). Furthermore, subsidies through safety net programs such PDS, ICDS, and MDM in India do not assure producers a consistent and reliable demand (given the vagaries of public procurement, which is based on a tendering system and is normally awarded to the lowest bidder, compromising the quality of the product and its acceptance). These deficiencies can be attributed to higher level policy barriers such as inadequate and irregular central and state government financing for distributing subsidized DFS through safety net programs and a weak institutional environment to develop and manage such interventions. Penetration through open markets requires attention to intensive marketing to communicate the benefits of the product and its benefits to the consumer. Various stakeholders would have to come together to address these issues from the producer's side that would set a string base to potentially scale the DFS programs horizontally or vertically. They would need to address strengthening institutional markets through public financing and demand creation through public service announcements as well as private marketing, managing cost and risks, and monitoring product quality to ensure consumer acceptance (29, 71).

The Government of India launched the "Anemia Mukt Bharat (India Free from Anemia)" initiative in the year 2018 (51). Under this initiative, several schemes were implemented to reduce anemia, namely providing iron supplements to vulnerable populations and fortifying foods with iron in rice, wheat flour, and salt, supplied through public programs (PDS, ICDS, and MDM) (52), which vary across states. The developed methodology would aid policymakers in evaluating varied potential iron fortification strategies and target populations based on region-specific factors.

In conclusion, iron fortification delivered through DFS under a universal program can improve wages and be sufficiently cost-effective for its implementation at scale in India. Our simulation results indicate that although anemia is less prevalent in men, anemic men are at a greater disadvantage due to opportunity costs related to income loss. For women, iron fortification coupled with improved sanitation is necessary for significant reductions in IDA. Future research to understand risk of long-term excess iron intake through fortification and the associated costs to avoid adverse health consequences is essential.

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