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Uncovering inequities in Covid-19 vaccine coverage for adults and elderly in Brazil: A multilevel study of 2021–2022 data

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ABSTRACT

Vaccination is crucial for reducing severe COVID-19 cases, hospitalizations, and deaths. However, vaccine access disparities within countries, particularly in low- and middle-income nations, may leave disadvantaged regions and populations behind. This study aimed to investigate potential inequalities in vaccine coverage among Brazilian aged 18 years and older based on demographic, geographic, and socioeconomic characteristics at the municipal level. A total of 389 million vaccination records from the National Immunization Program Information System were analyzed to calculate vaccine coverage rates for the first, second, and booster doses among adults (18–59 years) and elderly (60 + years) vaccinated between January 2021 and December 2022. We analyzed the data by gender and used a three-level (municipalities, states, regions) multilevel regression analysis to assess the association between vaccine coverage and municipal characteristics. Vaccination coverage was higher among the elderly than among adults, particularly for the second and booster doses. Adult women showed higher coverage rates than men (ranging from 118 % to 25 % higher along the analyzed period). Significant inequalities were observed when analyzing the evolution of vaccination coverage by sociodemographic characteristics of municipalities. In the early stages of the vaccination campaign, municipalities with higher per capita Gross Domestic Product (pGDP), educational level, and fewer Black residents reached higher population coverages earlier. In December 2022, adult and elderly booster vaccine coverage was 43 % and 19 %, respectively, higher in municipalities in the highest quintile of educational level. Higher vaccine uptake was also observed in municipalities with fewer Black residents and higher pGDP. Municipalities accounted for most of the variance in vaccine coverage (59.7 %-90.4 % depending on the dose and age group). This study emphasizes the inadequate booster coverage and the presence of socioeconomic and demographic disparities in COVID-19 vaccination rates. These issues must be addressed through equitable interventions to avoid potential disparities in morbidity and mortality.

1. Introduction

Vaccination constitutes an essential instrument in the ongoing battle against the COVID-19 pandemic, given its demonstrated efficacy in mitigating the incidence of severe cases of the disease, hospitalizations, long-term COVID-19 sequelae, and mortality rates [1]. The expedited development of COVID-19 vaccines, achieved through the implementation of rigorous clinical trials and regulatory procedures, represents a remarkable scientific and humanitarian accomplishment. Since December 2020, along with non-pharmacological measures, vaccination has played a decisive role in reducing the burden of COVID-19.

The effectiveness of vaccines is maximized when a large proportion of the population is vaccinated [2]. Ensuring high vaccination coverage is vital not only to safeguard the health of vaccinated individuals but also to curtail the transmission of the virus and protect those who cannot receive vaccines due to medical reasons

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or are at elevated risk for severe disease. In light of this, access to vaccines should be viewed as an inalienable right of every human being and a goal to be pursued by every community. Regrettably, there has been a profound discrepancy in the availability of vaccines and vaccination coverage between nations with higher and lower socioeconomic indicators. As of March 2021, about 20 % of the global population had access to nearly 95 % of the COVID-19 vaccines available worldwide, whereas the remaining 80 % had access to only around 5 % of the vaccines [3]. The unequal distribution of COVID-19 vaccines has persisted. As of March 2023, approximately 73 % of the population in high-income countries and 32 % of the population in low-income countries have received at least one dose of the vaccine [4].

In Brazil, the COVID-19 vaccination campaign has been publicly financed and coordinated. The federal government acquired vaccine doses and coordinated the national campaign. States have been tasked with decentralizing the distribution of doses to municipalities, and working collaboratively to define priorities and strategies within their territories. Municipalities, in turn, have been responsible for implementing vaccination strategies, which include vaccine conservation, organizing and managing vaccination sites, and recording and reporting the administered doses. Since the program's onset, and including the third dose booster campaign, older Brazilians and those with comorbidities and living in nursing home/long-term care facilities (LTCF) were prioritized, given their higher risk of hospitalization and death.

Despite the Brazilian health system being founded on the principles of universality and equity [5], the country has long struggled with social disparities in accessing healthcare services [6,7]. These inequities reflect the country's highly concentrated income distribution, which ranks Brazil as one of the most unequal nations in the world [8]. In this context, public policies that promote health equity are crucial. With regard to COVID-19, concerns have been raised that unequal access to vaccination may exacerbate previous health disparities. Studies conducted in different contexts, mostly in high-income countries, have identified that populations in positions of greater social vulnerability, as well as residents in regions with worse socioeconomic indicators, have lower vaccination coverage [9-11].

This concern is particularly alarming in Brazil, a country that has experienced a severe epidemiological impact from COVID-19. Despite representing only a fraction of the world's population (2.7 %), Brazil accounted for 10.2 % of global deaths during the pandemic [12]. Furthermore, as of March 2023, the disease has resulted in an official count of 37 million registered cases [12], exposing various challenges in the healthcare system, including a shortage of diagnostic tests and ICU beds in different locations and at different times of the pandemic.

Brazil has experienced inadequate management of the health crisis, marked by delays in vaccine procurement, logistical challenges, and vaccine hesitancy fueled by a disinformation campaign promoted by political and economic groups [13]. As a result, the country has faced challenges in achieving high Covid-19 vaccination coverage rates, except for the first two doses among the elderly. Monitoring vaccine coverage rates based on geographic and social characteristics is crucial for ensuring effective and equitable vaccination campaigns. Moreover, analyzing regional inequalities while considering the multilevel structure of the data can provide a more comprehensive understanding of the complex mechanisms driving regional disparities and the interaction of different levels in contributing to health outcomes.

The primary objective of our study was to investigate whether disparities exist in vaccine coverage among Brazilian adults and the elderly, based on demographic, geographic, and socioeconomic factors.

2. Methods

2.1. Vaccination data

In this study, we used vaccination records obtained from the National Immunization Program Information System (SI-PNI). The Brazilian Ministry of Health officially discloses this database through the openDataSUS platform and presents anonymized information on the application of vaccine doses for COVID-19 in the population. The available information includes data on the municipality and state individual's residency and vaccine application, date of application, vaccine type, gender, and age.

We have included in our analysis all individuals over 17 years of age vaccinated between January 16, 2021, and December 10, 2022. The records were classified into two groups: adults (from 18 to 59 years old) and elderly (60 years old or more). Entries with missing, incomplete, or inconsistent information accounted for 0.69 % of the total records and were excluded from the analysis.

We classified the dose type according to the order of the date of vaccine application in the same individual: first dose, second dose, and third dose (booster), as the dose classification provided by SI-PNI was often inconsistent. Next, we classified the records according to epidemiological week, order of vaccine application, gender, municipality, state, and region of residence of individuals. Vaccination data can be accessed from the following repository: https://github.com/covid19br/dados-vacinas.

2.2. Population data

To calculate vaccination coverage, as the denominator we used the data on the resident population calculated by the Ministry of Health (MS) (https://tabnet.datasus.gov.br/cgi/deftohtm.exe?ibge/cnv/popsvsbr.def). As of March 2023, the most recent census with consolidated and available data in Brazil was from 2010. Therefore, in partnership with the Brazilian Institute of Geography and Statistics (IBGE), the MS used data from census years and population projections to estimate the resident population in each Brazilian municipality according to gender and age group for intercensus years. The number of adult residents (aged 18 to 59 years) and elderly residents (aged 60 years or older) in Brazilian municipalities were consolidated by converging with official population statistics, territorial compatibility, and methodological compatibility produced for the estimates [14].

2.3. Municipal socioeconomic and demographic data

The educational and racial composition data of Brazilian municipalities were obtained from the national census of 2010 and published by the Brazilian Institute of Geography and Statistics (IBGE). These indicators were also disseminated in the Human Development Atlas of Brazil, which was jointly built by the United Nations Development Programme (UNDP), the Institute of Applied Economic Research (IPEA), and the João Pinheiro Foundation (FJP) (https://www.atlasbrasil.org.br/).

The educational indicator used in this study was the average number of years of schooling that a generation of children entering school is expected to complete by the age of 18, assuming that current standards are maintained throughout their school life. The racial composition of each municipality was calculated by dividing the number of Black residents (including those who identify as Black or brown) by the total number of residents in that municipality. In Brazilian censuses, racial information is self-reported and classified as Black, brown, white, yellow, or indigenous. The Gross Domestic Product (GDP) per capita of each Brazilian municipality was calculated for 2018 by IBGE in partnership with state statistical agencies, state secretariats of government, and the Superintendence of the Manaus Free Trade Zone. All three variables described above (educational level, racial composition, and GDP per capita) were divided into quintiles based on their distribution across the municipalities. To classify municipalities by population size, we used estimates released by the Brazilian Ministry of Health in 2021. The municipalities were grouped into five categories based on their population size: up to 9,999 inhabitants, 10,000 to 19,999 inhabitants, 20,000 to 49,999 inhabitants, 50,000 to 99,999 inhabitants, and 100,000 or more inhabitants.

2.4. Data analysis

To calculate the vaccine coverage, we divided the number of vaccinated individuals, as recorded in SI-PNI, by the resident population in each age and gender group within each municipality, and then multiplied the result by 100. We initially estimated the values for each dose by gender for all weeks in 2021 and 2022. These results were then plotted in radar charts, and the absolute and relative differences in vaccination between women and men were calculated. The relative differences were calculated by dividing the values observed among women by those observed among men. Next, we analyzed different indicators according to the socioeconomic and demographic characteristics of the municipalities. We initially described the vaccination coverage for each dose during the epidemiological weeks spanning from January 2021 to December 2022. We then calculated the rate of increase in vaccination coverage for the extreme quintiles (Q1 and Q5) of the socioeconomic and demographic (SED) variables each week. These values, expressed in percentage points, represent the difference in coverage between the week under analysis and the previous week. We also described the absolute and relative differences in coverage between Q1 and Q5 for the months of June 2021, December 2021, June 2022, and December 2022, for both the first and second doses. As the booster dose was only introduced in November 2021 in the vaccination campaign, we measured inequality for this dose in December 2021, June 2022, and December 2022.

Our data had a hierarchical structure consisting of three levels: municipalities, states, and regions. We used multilevel linear models to analyze vaccine coverage as a continuous variable, with random effects included for municipalities, states, and regions [15]. The independent variables were the socioeconomic and demographic characteristics of the municipalities. We focused on the COVID-19 vaccine coverage values observed in the last month of our study period, December 2022, for this analysis.

To determine the proportion of variance attributed to each level, we calculated the division of the observed variance at that level by the sum of the observed variances in the three analyzed levels. We then multiplied the quotient by 100 to obtain the percentage of variance attributed to each level, denoted as z. The formula for calculating z was as follows:

$$(\mathrm{Var}(z)/(\mathrm{Var}(\mathrm{region}) + \mathrm{Var}(\mathrm{state}) + \mathrm{Var}(\mathrm{county}))) \times 100$$

This study adhered to the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guideline. As we used publicly available ecological data aggregated by geographic units, the present study did not require an ethics committee review.

3. Results

During the analyzed period, Brazil administered 303 million first, second and third doses of the vaccine in adults and 85 million doses in the elderly. Vaccination coverage in December 2022 was higher among the elderly compared to adults, particularly in the second dose (94.5 % vs. 86.3 %, respectively) and booster dose (79.7 % vs. 52.3 %) (Supplementary Table 1). The values were very similar comparing both age groups when analyzing the first dose (98.4 % vs. 97.4 %). Adults and elderly presented significantly lower coverage for the booster dose. Regarding the country's sociodemographic characteristics, according to the 2010 census, 50.9 % of the population was Black, the expected years of schooling at age 18 was 9.5 years, and nearly one-third of the country's municipalities had less than 20,000 inhabitants.

Gender differences in vaccination coverage are described in Fig. 1 and Supplementary Tables 2 and 3. Women showed higher vaccination coverage among adults in all three vaccine doses, with an increasing gap between men and women as new vaccine doses were incorporated. In December 2022, booster dose coverage among adults was 25 % higher among women (a difference equivalent to 11.6 percentage points). In the elderly population, vaccination coverage was very similar, with slightly higher coverage among men for the first and second doses and among women for the booster dose.

When analyzing the evolution of vaccination coverage according to sociodemographic characteristics of the municipalities, profound inequalities can be observed. Supplementary Figs. 1-4 show the increase in vaccination coverage achieved each epidemiological week in different groups of municipalities. Among the adult population, it is clear in all three vaccine doses that there is a higher increase in the vaccinated population among municipalities with higher educational levels, higher per capita GDP, and a lower proportion of the Black population. The same pattern is observed in the booster dose for the elderly, but there were no significant differences in the first and second doses for this age group.

Municipalities with better socioeconomic indicators, a lower proportion of the Black population, and at the extremes of population size continued to have higher vaccination coverage during all epidemiological weeks of 2021 and 2022 (Fig. 2 and Supplementary Figs. 5–8). In the case of the booster dose (Fig. 2), in the quintile of municipalities with higher expected years of schooling at age 18, vaccination coverage among adults was 58.7 % in December 2022, a value that only reached 41.2 % in the quintile with the lowest educational level. In the same month, the values were 54.5 % and 43.9 % in municipalities with the lowest and highest proportion of the Black population, respectively. Regarding the elderly population, booster dose coverage was 82.9 % in the quintile of municipalities with highest per capita GDP and 70.8 % in the quintile with lowest per capita GDP in December 2022.

The relative and absolute inequalities between the extreme quintiles of the sociodemographic indicators throughout the vaccination campaign are described in Table 1. The disparities between municipalities were consistently larger among adults, and the relative differences between the extreme quintiles were particularly pronounced in the booster dose. A reduction in relative inequalities over the months was observed, but in the last semester analyzed there was only minor fluctuation in absolute differences in most ages and doses. Among adults, the booster dose had a coverage 43 %, 21 %, and 24 % higher in municipalities with better educational, income, and lower proportion of Black population indicators in December 2022, respectively. One year earlier (December 2021), about one month after the start of booster dose application in this age group, the differences were even greater, reaching 113 %, 64 %, and 77 %, respectively. Among the elderly, the differences were smaller but still significant, especially in the booster dose. Municipalities with a lower proportion of the Black population, higher educational level, and higher per capita GDP had significantly higher vaccination coverage compared to municipalities in the other extreme of the distribution. Specifically, vaccination coverage in these municipalities was 9.7, 13.3, and 12.2 percentage points higher than in the lower-performing quintiles.

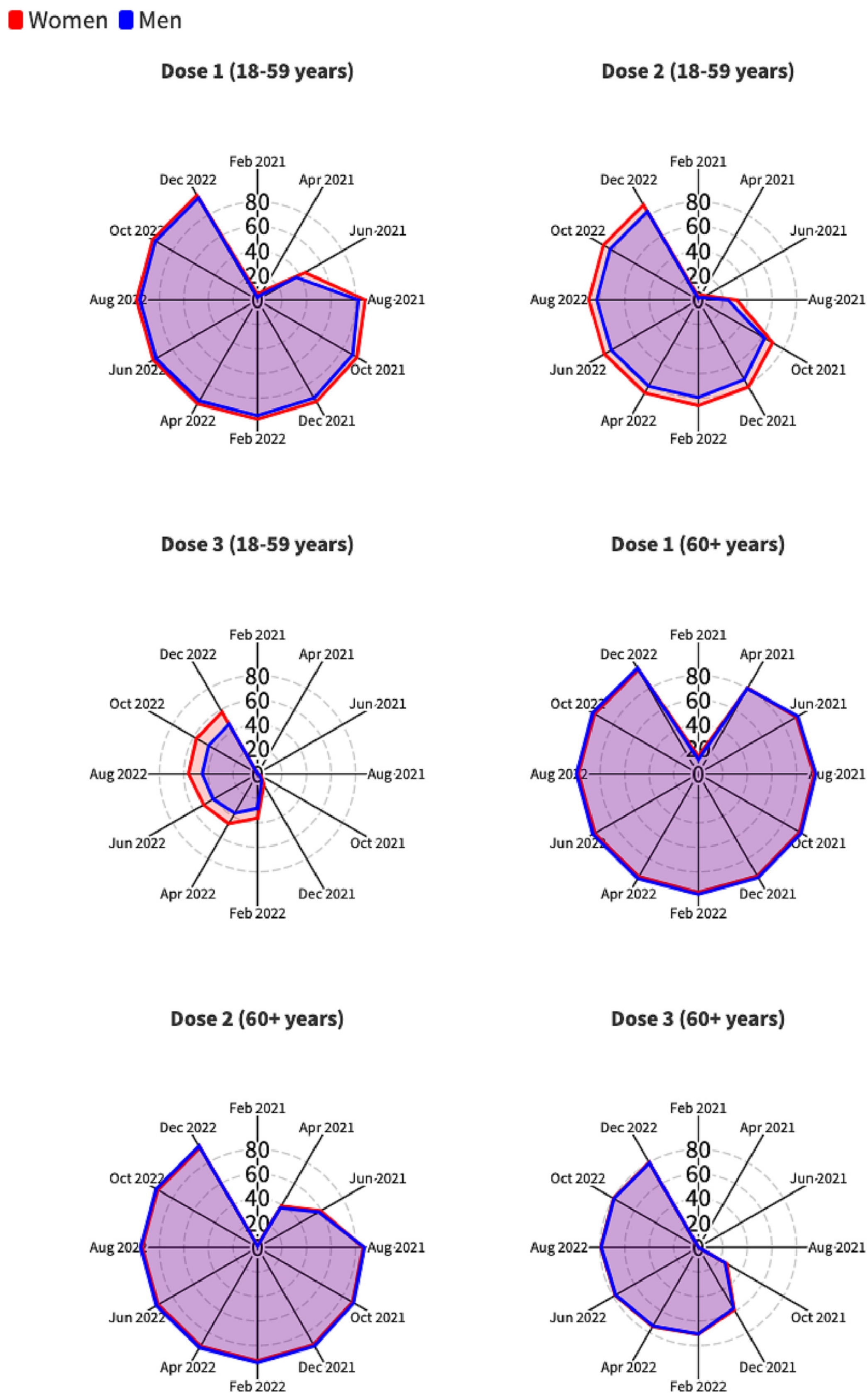

Fig. 1. Covid-19 vaccine coverage (%) according to gender, dose, age group, and month. Brazil, 2021–2022.

Multilevel analysis revealed statistically significant associations between all variables, as shown in Supplementary Table 4 (crude analysis) and Table 2 (adjusted analysis). Inequality was observed across all doses and age groups, with a clear dose–response effect. When analyzing the booster dose among adults, the adjusted β coefficient was 6.67 (95 % CI 5.08; 8.25) for the quintile with the

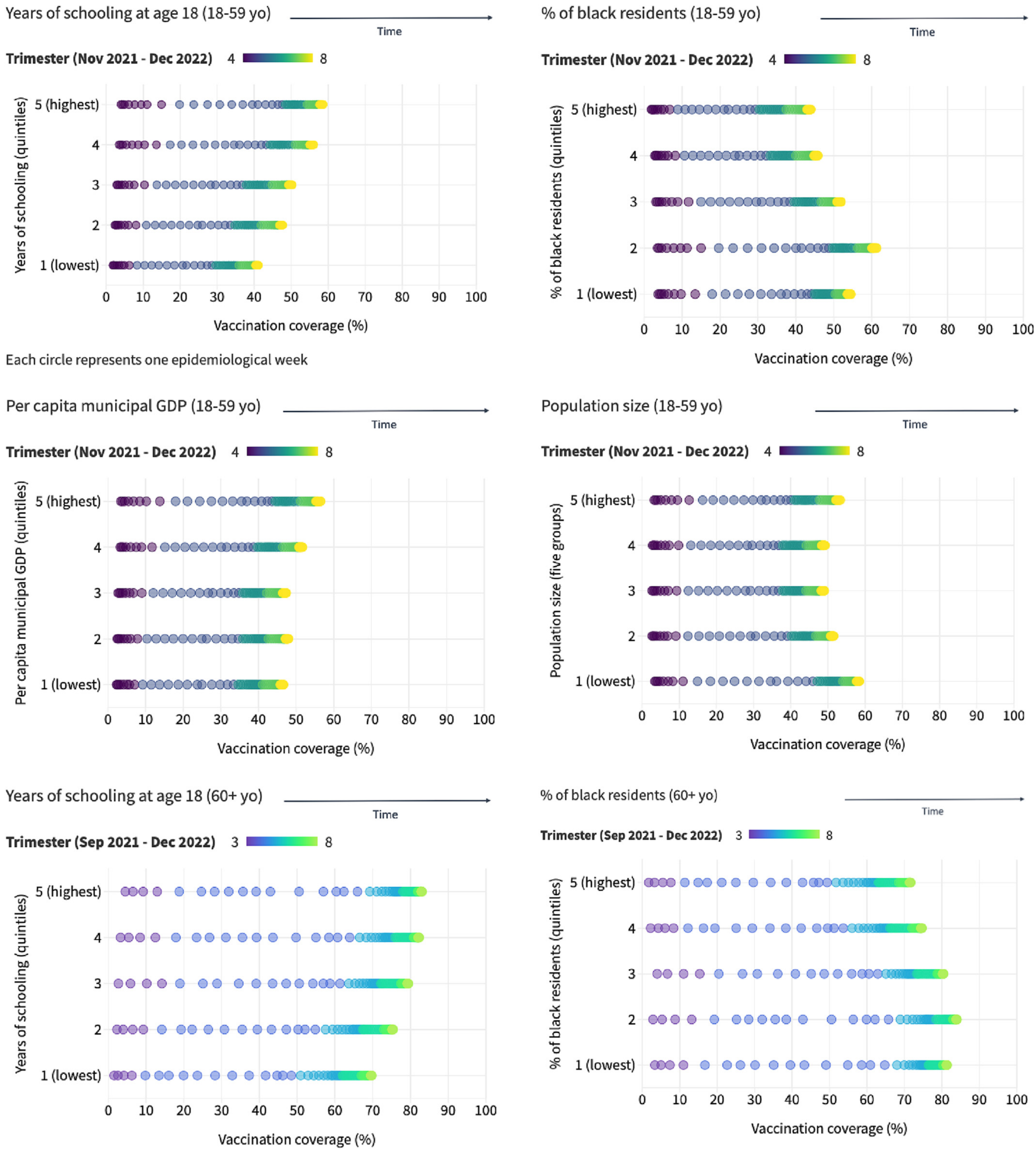

Fig. 2. Covid-19 vaccine booster dose coverage (%) according to the quintiles of expected years of schooling at 18, proportion (%) of Black residents, per capita municipal Gross Domestic Product (GDP), population size, epidemiological week and age group. Brazilian municipalities, 2021–2022.

highest education level, and 4.50 (95 % CI 2.98; 6.03) among the elderly. Additional adjusted coefficient values can be found in Table 2. The study also found that municipalities, as compared to states and regions, were the largest source of variation in vaccination coverage across all doses and age groups, as presented in Table 3. In particular, municipalities accounted for approximately 60 % of the variance in booster dose coverage, a figure even higher in doses 1 and 2.

4. Discussion

Our study observed that municipalities with higher per capita GDP, higher educational level and lower proportion of Black population had higher covid-19 vaccination coverage throughout 2021 and 2022. Such inequalities between municipalities were always greater among adults compared to the elderly, and were more pronounced in the booster dose compared to the first two doses.

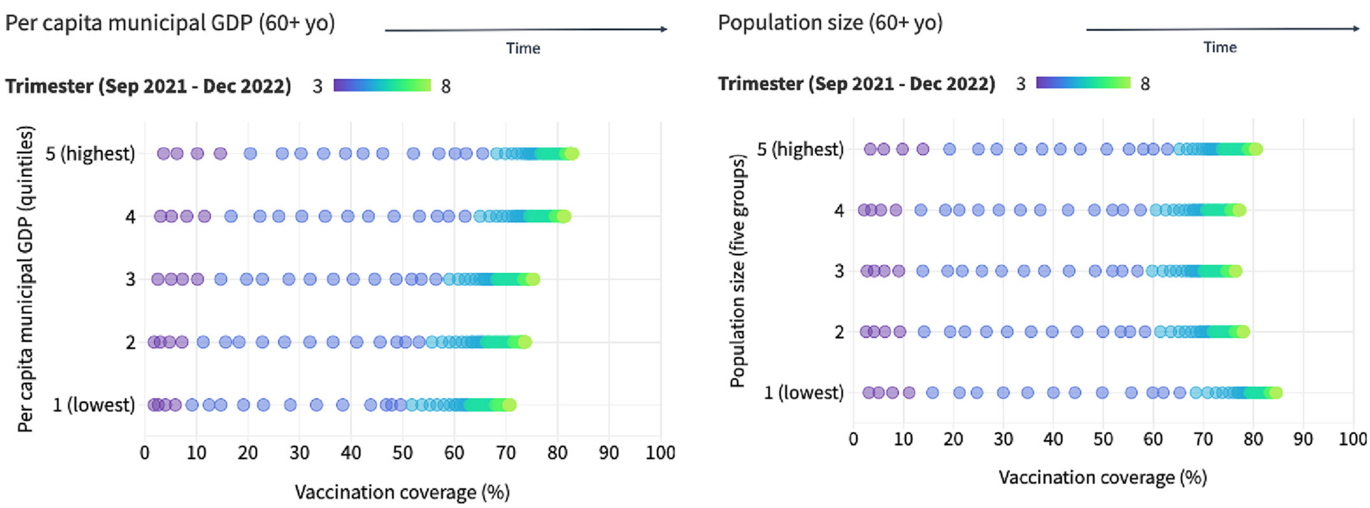

Fig. 2 (*continued*)

Table 1
Relative and absolute differences of covid-19 vaccine coverage comparing the values of the extreme quintiles of expected years of schooling at 18, proportion (%) of Black residents, per capita municipal Gross Domestic Product (GDP) and groups of populational size. Brazilian municipalities, 2021–2022.

	Expected years of schooling at 18 years old		Proportion of Black residents		Per capita municipal GDP		Population size	
	Q5 / Q1	Q5 – Q1	Q1 / Q5	Q1 – Q5	Q5 / Q1	Q5 – Q1	G1 / G5	G1 – G5
18–59 years-old								
1st dose								
June/2021	1.27	5.30	1.23	4.69	1.22	4.51	1.01	0.18
December/2021	1.17	14.56	1.14	11.71	1.14	12.05	1.07	6.52
June/2022	1.14	12.38	1.10	9.33	1.11	9.92	1.07	6.43
December/2022	1.13	11.95	1.10	8.87	1.11	9.58	1.07	6.39
2nd dose								
June/2021	1.41	1.60	1.56	1.96	1.43	1.53	0.94	–0.27
December/2021	1.32	20.51	1.27	17.55	1.22	14.55	1.10	7.87
June/2022	1.25	18.00	1.19	14.45	1.17	12.89	1.09	7.52
December/2022	1.23	17.38	1.17	13.55	1.16	12.58	1.08	7.12
3rd dose (booster)								
December/2021	2.13	3.24	1.77	2.27	1.64	2.12	0.94	–0.29
June/2022	1.53	18.20	1.37	13.12	1.24	9.47	1.15	6.63
December/2022	1.43	17.52	1.24	10.59	1.21	9.89	1.10	5.12
60 years-old								
1st dose								
June/2021	1.09	7.39	1.05	4.76	1.11	9.34	0.98	–1.88
December/2021	1.05	4.82	1.03	2.39	1.09	8.24	0.99	–0.96
June/2022	1.04	3.70	1.01	1.28	1.08	7.14	0.99	–0.97
December/2022	1.04	3.38	1.01	0.95	1.07	6.87	0.99	–0.95
2nd dose								
June/2021	1.09	4.36	1.04	2.22	1.08	3.99	1.02	1.29
December/2021	1.11	9.12	1.08	7.09	1.13	11.11	1.03	2.93
June/2022	1.08	7.09	1.06	4.93	1.11	9.32	1.03	2.59
December/2022	1.07	6.57	1.05	4.34	1.10	8.76	1.03	2.52
3rd dose (booster)								
December/2021	1.36	13.25	1.28	10.61	1.36	13.70	0.98	–0.89
June/2022	1.23	15.33	1.18	12.29	1.21	13.74	1.06	4.61
December/2022	1.19	13.30	1.14	9.70	1.17	12.16	1.05	3.97

Q1: quintile 1 of the variable distribution; Q5: quintile 5 of the variable distribution; G1: group 1 of municipal populational size (up to 9,999 inhabitants); G5: group 5 of municipal populational size (more than 99,999 inhabitants).

Women showed higher vaccination coverage than men in all three vaccine doses among adults, with an increasing gap between men and women as new vaccine doses were incorporated in the campaign. Multilevel analysis revealed that municipalities accounted for the majority of the variance observed in vaccine coverage.

Higher vaccination coverage in areas with better socioeconomic indicators was observed within high-income countries [10,16,17]. In Brazil, however, inequality was established right from the beginning of the vaccination campaign and was not reversed in the following months. Residents in municipalities with a higher proportion of Black population and worse socioeconomic indicators may face greater difficulty in accessing the healthcare system, whether due to geographic barriers, financial constraints for commuting, or greater difficulty in taking time off work. Health

Table 2

Adjusted multilevel regression coefficients of covid-19 vaccine coverage according to municipal socioeconomic and demographic variables according to age groups and vaccine dose. Brazil, 2021–2022.

	Adjusted β coefficient ($CI^{‡}_{95\%}$)					
	18–59 years old			60 + years old		
	Dose 1	Dose 2	Dose 3	Dose 1	Dose 2	Dose 3
Expected years of schooling at 18 years old						
Quintile 1 (lowest)	1.00	1.00	1.00	1.00	1.00	1.00
Quintile 2	2.56 (1.05–4.06)	2.85 (1.50;4.21)	2.57 (1.33;3.81)	0.91 (−0.32;2.14)	1.47 (0.29;2.64)	2.60 (1.41;3.80)
Quintile 3	3.51 (1.93;5.09)	3.93 (2.51;5;35)	3.83 (2.54;5.13)	0.60 (−0.69;1.89)	1.19 (−0.04;2.42)	2.93 (1.68;4.18)
Quintile 4	4.29 (2.58;6.00)	5.01 (3.47;6.55)	4.96 (3.56;6.37)	1.36 (−0.04;2.75)	2.12 (0.78;3.45)	4.10 (2.74;5.46)
Quintile 5 (highest)	6.10 (4.17;8.02)	7.14 (5.40;8.87)	6.67 (5.08;8.25)	0.91 (−0.67;2.48)	1.89 (0.39;3.40)	4.50 (2.98;6.03)
Proportion of Black residents						
Quintile 1 (lowest)	1.00	1.00	1.00	1.00	1.00	1.00
Quintile 2	−1.44 (−3.27;0.39)	−1.98 (−3.62;−0.33)	−0.66 (−2.16;0.85)	−1.21 (−2.70;0.29)	−1.51 (−2.94;−0.08)	−0.91 (−2.36;0.54)
Quintile 3	−3.90 (−6.13;−1.67)	−4.72 (−6.74;−2.71)	−3.31 (−5.15;−1.47)	−1.15 (−2.97;0.66)	−1.58 (−3.32;0.16)	−1.62 (−3.39;0.16)
Quintile 4	−6.84 (−9.23;−4.44)	−8.55 (−10.71;−6.39)	−8.40 (−10.38;−6.42)	−3.45 (−5.41;−1.50)	−4.36 (−6.23;−2.50)	−6.10 (−8.00;−4.19)
Quintile 5 (highest)	−8.55 (−11.13;−5.98)	−9.59 (−11.92;−7.26)	−8.54 (−10.67;−6.40)	−5.86 (−7.96;−3.76)	−6.10 (−8.11;−4.09)	−6.70 (−8.76;−4.65)
Per capita municipal GDP						
Quintile 1 (lowest)	1.00	1.00	1.00	1.00	1.00	1.00
Quintile 2	4.02 (2.45;5.60)	3.36 (1.94;4.78)	0.44 (−0.85;1.74)	4.86 (3.57;6.14)	4.23 (3.01;5.46)	2.23 (0.98;3.48)
Quintile 3	5.58 (3.74;7.42)	5.49 (3.83;7.14)	2.50 (0.98;4.01)	7.80 (6.30;9.30)	7.56 (6.13;9.00)	5.34 (3.88;6.80)
Quintile 4	8.69 (6.65;10.72)	8.40 (6.57;10.22)	3.52 (1.86;5.19)	10.10 (8.44;11.76)	9.96 (8.37;11.54)	7.34 (5.73;8.95)
Quintile 5 (highest)	11.24 (9.14;13.35)	10.35 (8.45;12.24)	3.61 (1.88;5.34)	12.50 (10.78;14.22)	12.04 (10.40;13.68)	8.55 (6.88;10.22)
Municipal population size (inhabitants)						
minimum – 9,999	1.00	1.00	1.00	1.00	1.00	1.00
10,000 – 19,999	−7.00 (−8.24;−5.76)	−7.51 (−8.62;−6.40)	−7.58 (−8.59;−6.56)	−4.93 (−5.94;−3.92)	−5.14 (−6.11;−4.18)	−6.15 (−7.13;−5.17)
20,000 – 49,999	−7.79 (−9.14;−6.45)	−9.23 (−10.44;−8.02)	−9.64 (−10.75;−8.74)	−4.91 (−6.01;−3.81)	−5.79 (−6.84;−4.74)	−7.78 (−8.84;−6.72)
50,000 – 99,999	−9.49 (−11.54;−7.44)	−11.13 (−12.97;−9.29)	−11.65 (−13.3;−9.97)	−5.17 (−6.85;−3.50)	−6.24 (−7.84;−4.64)	−8.87 (−10.49;−7.24)
100,000 - maximum	−12.04 (−14.22;−9.87)	−13.83 (−15.78;−11.87)	−13.33 (−15.11;−11.55)	−5.85 (−7.63;−4.07)	−7.24 (−8.94;−5.54)	−10.02 (−11.74;−8.30)

Table 3
Variance estimates (VE), standard errors (SE) and variance partition coefficient (VPC) in multilevel null model in covid-19 vaccine coverage according to age groups and vaccine dose. Brazil, December 2022.

	Region			State			Municipality		
Age	VE	SE	VPC (%)	VE	SE	VPC (%)	VE	SE	VPC (%)
18–59 years-old									
1st dose	37.50	28.27	9.38	31.73	11.20	7.93	330.66	6.28	82.69
2nd dose	88.52	61.89	21.68	43.57	14.19	10.67	276.18	5.25	67.65
3rd dose	85.87	62.68	22.12	70.71	22.28	18.21	231.64	4.40	59.67
60 + years-old									
1st dose	1.65	4.57	0.68	21.55	8.03	8.90	219.03	4.16	90.42
2nd dose	16.08	13.71	6.63	24.97	8.59	10.29	201.65	3.83	83.09
3rd dose	68.36	49.23	21.09	45.85	14.76	14.15	209.90	3.99	64.76

services in these municipalities may have had a poorer structure and care flow prior to 2020, in addition to lower financial resources to combat the pandemic and fewer healthcare teams to offer vaccines and conduct active population searches. Previous studies have shown that expenditure on Primary Healthcare (PHC) in Brazil until 2019 was lower in municipalities with greater socioeconomic deprivation [18], and the structure of basic health units was worse in municipalities with lower Human Development Index [19]. Additionally, initiatives to address vaccine confidence are essential to increase vaccine coverage and reduce inequalities, as disinformation campaigns can disproportionately affect vulnerable regions and people in situations of greater vulnerability [20].

By assessing vaccine coverage starting from six months after the onset of the vaccination program and up until December 2022, we identified that considerable advances were made in ensuring that the elderly were protected for both the first and second doses, even in the most vulnerable municipalities, but there was considerable delay in reaching this population if the municipality was poorer, had a higher share of Black population and lower formal schooling. The results show that the Ministry of Health's vaccination program failed to meet these same target in this highly vulnerable population with respect to the third booster dose, which was introduced in November 2021, just prior to a major omicron wave. Considering the start of vaccination, and up until 12 months after the start of the campaign, there were high percentages of the elderly that were not boosted. In contrast to countries such as Singapore and Japan which successfully vaccinated and boosted the elderly, our findings coincide with patterns observed in China where booster coverage level drops were observed for older adults. Both demand and supply factors have been cited for the lack of coverage.

In Brazil, the vaccination campaign initially focused on the elderly. During the first few months, widespread social mobilization and higher risk perception may have contributed to almost universal coverage for the first doses in this age group. However, in the following months of 2021 and 2022, the spread of disinformation campaigns regarding vaccines and less emphasis on social communication channels about the risks of infection and the importance of vaccination occurred. This, combined with lower risk perception and deprioritization by municipalities in their vaccination campaigns, may have resulted in lower booster coverage among the elderly and lower coverage of all vaccine doses among adults. It is worth noting, also, that adults tend to report lower risk perceptions of COVID-19 compared to the elderly [21]. In addition, the discourse of political and health authorities in Brazil questioning the safety and effectiveness of vaccines, extensively reverberated through social media, may have had an impact on adherence to vaccination. Lastly, vaccination schedules - times when each age group would be entitled to vaccination - and the different vaccination protocols given the mix of vaccines from different platforms have become very complex over the years, which may also have increased vaccine hesitancy.

Previous studies have produced mixed results regarding vaccination uptake against COVID-19 by gender [22–24]. In our study, a small difference was observed among the elderly, but among adults, we found significantly greater coverage among women. This pattern is similar to what Diesel et al. [25] observed during the first months of vaccination in the US. Studies that compared male and female behaviors during pandemics prior to the one caused by SARS-CoV-2 showed that women were more likely to carry out preventive and avoidant behaviors, partly due to feeling more susceptible [26]. The result observed in Brazil can be explained by social and behavioral aspects in the country. Women tend to have greater contact with health services including for routine appointments and other types of medical care. In Brazil, the proportion of women who attended a medical consultation in the last 12 months is almost 20 % higher than that among men, for example [7]. This closer contact with health services can increase their familiarity and confidence in health services. Conversely, the culture that emphasizes masculine toughness and strength can impact men's conduct and result in a less proactive approach toward their health. Women constitute a significant proportion of the healthcare workforce, and a recent study examining the intention to receive a COVID-19 vaccine found that female health professionals had a higher acceptance rate than their male counterparts [27]. Public opinion surveys also suggest that women were more aware and decided about the importance of vaccination in a national context of strong politicization [28]. Such findings have important policy implications in alerting that vaccine campaigns need to better target men more generally, among adults especially.

In Brazil, vaccine campaigns are implemented at the municipal level, which may explain the greater variance of outcomes at this geographic level. It is up to the municipalities to identify and overcome the barriers that make it difficult to vaccinate the population residing in the area. However, a significant part of the variance is also attributed to states and regions. The more active participation of state management can accelerate and improve the distribution of vaccines, and enable actions to identify municipalities with difficulties in achieving good vaccine coverage, providing technical or financial support as needed. Furthermore, collaboration between adjacent states can facilitate the exchange of successful experiences that are adapted to the social and cultural realities of the region. By working together, states and regions can effectively coordinate their efforts to ensure greater vaccination coverage and reduce inequities in access to vaccines.

The present study has some limitations that should be taken into account. Firstly, the registration of the vaccine doses by municipalities in the SI-PNI system faced some problems, including delays and filling errors. Nonetheless, the SI-PNI is a robust and reliable system overall. The data analyzed were obtained from the Ministry of Health in March 2023, three months after the last epidemiological week analyzed. This time lapse allowed for the inclusion of data that may have been delayed. Furthermore, registration issues are not typically systemic at the national level.

Another limitation concerns the population data used in this study. The data were provided by the Ministry of Health of Brazil, but they are based on the last census carried out in Brazil in 2010. Therefore, there may be underestimations or overestimations of the resident population in some municipalities. Similarly, the municipal educational information and racial composition data are based on the 2010 census, and it should be noted that these values may have undergone significant variations across municipalities over the span of a decade.

The persistent subnational inequalities in vaccination coverage over nearly two years and the decline in the proportion of the population covered as new doses were added to the vaccination schedule are deeply concerning. In a country with profound socioeconomic disparities and during one of the most severe pandemics in human history, failures occurred at all levels of management, particularly the lack of coordination by the federal government in managing the crisis. Furthermore, the government (union, states, municipalities) did not monitor vaccination coverage inequalities as the vaccination campaign progressed, which prevented the design and implementation of equitable policies. The country needs to structure public policies that incorporate the measurement of inequalities in its guidelines and commit to acting to achieve equity. Another critical issue is the low booster vaccination coverage among the elderly and the low coverage of all doses among adults, especially among the residents of municipalities with a higher proportion of Black population and worse socioeconomic indicators. These populations are at high risk of severe COVID-19 disease and long-term complications due to low vaccination coverage.

Data availability

Link to the dataset is provided in the Methods section

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.vaccine.2023.05.030.

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