Supplementary material: SARS-CoV-2 infection fatality rates in India: systematic review, meta-analysis and model-based estimation

Supplementary Appendices

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Appendix A. PRISMA checklist [1]

Section and Topic	Item #	Checklist item	Location where item is reported
TITLE			
Title	1	Identify the report as a systematic review.	Title Page
ABSTRACT			
Abstract	2	Background: Provide an explicit statement of the main objective(s) or question(s) the review addresses. Methods: Specify the inclusion and exclusion criteria for the review. Specify the information sources (e.g. databases, registers) used to identify studies and the date when each was last searched. Specify the methods used to assess risk of bias in the included studies. Specify the methods used to present and synthesise results. Results: Give the total number of included studies and participants and summarise relevant characteristics of studies. Present results for main outcomes, preferably indicating the number of included studies and participants for each. If meta-analysis was done, report the summary estimate and confidence/credible interval. If comparing groups, indicate the direction of the effect (i.e. which group is favoured). Discussion: Provide a brief summary of the limitations of the evidence included in the review (e.g. study risk of bias, inconsistency and imprecision). Provide a general interpretation of the results and important implications. Other: Specify the primary source of funding for the review. Provide the register name and registration number.	Title Page
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of existing knowledge.	3-6
Objectives	4	Provide an explicit statement of the objective(s) or question(s) the review addresses.	6
METHODS			
Eligibility criteria	5	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses.	11-12
Information sources	6	Specify all databases, registers, websites, organisations, reference lists and other sources searched or consulted to identify studies. Specify the date when each source was last searched or consulted.	10-11, App B
Search strategy	7	Present the full search strategies for all databases, registers and websites, including any filters and limits used.	App B
Selection process	8	Specify the methods used to decide whether a study met the inclusion criteria of the review, including how many reviewers screened each record and each report retrieved, whether they worked independently, and if applicable, details of automation tools used in the process.	13, App B
Data collection process	9	Specify the methods used to collect data from reports, including how many reviewers collected data from each report, whether they worked independently, any processes for obtaining or confirming data from study investigators, and if applicable, details of automation tools used in the process.	13, App B
Data items	10a	List and define all outcomes for which data were sought. Specify whether all results that were compatible with each outcome domain in each study were sought (e.g. for all measures, time points, analyses), and if not, the methods used to decide which results to collect.	7-10, 13
	10b	List and define all other variables for which data were sought (e.g. participant and intervention characteristics, funding sources). Describe any assumptions made about any missing or unclear information.	7-10, 13
Study risk of bias assessment	11	Specify the methods used to assess risk of bias in the included studies, including details of the tool(s) used, how many reviewers assessed each study and whether they worked independently, and if applicable, details of automation	15

Section and Topic	Item #	Checklist item	Location where item is reported
		tools used in the process.	
Effect measures	12	Specify for each outcome the effect measure(s) (e.g. risk ratio, mean difference) used in the synthesis or presentation of results.	14, App F
Synthesis methods	13a	Describe the processes used to decide which studies were eligible for each synthesis (e.g. tabulating the study intervention characteristics and comparing against the planned groups for each synthesis (item #5)).	App F, App G
	13b	Describe any methods required to prepare the data for presentation or synthesis, such as handling of missing summary statistics, or data conversions.	14, App F, App G
	13c	Describe any methods used to tabulate or visually display results of individual studies and syntheses.	13-15, App F
	13d	Describe any methods used to synthesize results and provide a rationale for the choice(s). If meta-analysis was performed, describe the model(s), method(s) to identify the presence and extent of statistical heterogeneity, and software package(s) used.	13-15, App F
	13e	Describe any methods used to explore possible causes of heterogeneity among study results (e.g. subgroup analysis, meta-regression).	13-15
	13f	Describe any sensitivity analyses conducted to assess robustness of the synthesized results.	15
Reporting bias assessment	14	Describe any methods used to assess risk of bias due to missing results in a synthesis (arising from reporting biases).	15
Certainty assessment	15	Describe any methods used to assess certainty (or confidence) in the body of evidence for an outcome.	10, 15
RESULTS			
Study selection	16a	Describe the results of the search and selection process, from the number of records identified in the search to the number of studies included in the review, ideally using a flow diagram.	17-19
	16b	Cite studies that might appear to meet the inclusion criteria, but which were excluded, and explain why they were excluded.	22, App D, App E, App G
Study characteristics	17	Cite each included study and present its characteristics.	19-22
Risk of bias in studies	18	Present assessments of risk of bias for each included study.	App I
Results of individual studies	19	For all outcomes, present, for each study: (a) summary statistics for each group (where appropriate) and (b) an effect estimate and its precision (e.g. confidence/credible interval), ideally using structured tables or plots.	20, App C
Results of syntheses	20a	For each synthesis, briefly summarise the characteristics and risk of bias among contributing studies.	37, App I
	20b	Present results of all statistical syntheses conducted. If meta-analysis was done, present for each the summary estimate and its precision (e.g. confidence/credible interval) and measures of statistical heterogeneity. If comparing groups, describe the direction of the effect.	29-37
	20c	Present results of all investigations of possible causes of heterogeneity among study results.	33-36
	20d	Present results of all sensitivity analyses conducted to assess the robustness of the synthesized results.	37-38, App H
Reporting biases	21	Present assessments of risk of bias due to missing results (arising from reporting biases) for each synthesis assessed.	37, App J
Certainty of evidence	22	Present assessments of certainty (or confidence) in the body of evidence for each outcome assessed.	37, App J
DISCUSSION			

Section and Topic	Item #	Checklist item	Location where item is reported
Discussion	23a	Provide a general interpretation of the results in the context of other evidence.	42-45
	23b	Discuss any limitations of the evidence included in the review.	45-46
	23c	Discuss any limitations of the review processes used.	45-46
	23d	Discuss implications of the results for practice, policy, and future research.	46-50
OTHER INFORMATION			
Registration and protocol	24a	Provide registration information for the review, including register name and registration number, or state that the review was not registered.	NA
	24b	Indicate where the review protocol can be accessed, or state that a protocol was not prepared.	NA
	24c	Describe and explain any amendments to information provided at registration or in the protocol.	NA
Support	25	Describe sources of financial or non-financial support for the review, and the role of the funders or sponsors in the review.	Title Page
Competing interests	26	Declare any competing interests of review authors.	Title Page
Availability of data, code and other materials	27	Report which of the following are publicly available and where they can be found: template data collection forms; data extracted from included studies; data used for all analyses; analytic code; any other materials used in the review.	38, App C

NA = not applicable.

Appendix B. Systematic review search procedure

To conduct the present systematic review, we systematically collected publications and preprints concerning infection fatality rates (IFRs) from SARS-CoV-2 in India and neighboring countries of Bangladesh, Nepal, Pakistan, and Sri Lanka. To identify relevant papers, we searched four databases: PubMed, Embase, Global Index Medicus, and isearch for preprints (encompassing bioRxiv, medRxiv, and SSRN). The search was conducted on July 3, 2021 and, as such, the results reflect published studies and preprints available from January 1, 2020 to July 3, 2021. Results were further verified through August 15, 2021 through reviewing media reports, government press releases, and manual search of preprints and publications. Data were extracted from the online search engines into the reference manager Zotero, deduplicated, and imported into Excel for screening.

The title/abstract screening, the full-text screening, and data abstraction were independently performed by two screeners to verify which studies met inclusion and exclusion criteria and to very data collected. When the two screeners disagreed on the marking for a citation, the screeners reached a consensus on whether to advance the citation to the next level of screening. Below we publish the full search strategies for each database.

PubMed (National Library of Medicine)

Date searched: 7/3/2021
Number of results: 2,940
Date filter: January 1, 2020 to [blank]
Other filters applied: None

1.
covid-19[tw] OR COVID19[tw] OR SARS-CoV-2[tw] OR SARS-CoV2[tw] OR severe acute respiratory syndrome coronavirus 2[tw] OR 2019-nCoV[tw] OR 2019nCoV[tw] OR coronavirus[tw] OR coronavirus[mh] OR covid-19[mh]

2.
india[text word] OR india[mesh] OR indian[text word] OR pakistan[text word] OR pakistani[text word] OR pakistan[mesh] OR bangladesh[text word] OR bangladeshi[text word] OR bangladesh[mesh] OR nepal[text word] OR nepal[mesh] OR "sri lanka"[text word] OR “sri lankan”[text word] OR “sri lanka”[mesh]

3.
IFR[text word] OR infection*[text word] OR CFR[text word] OR case*[text word] OR transmission*[text word] OR mortalit*[text word] OR mortality[mesh] OR fatalit*[text word] OR lethalit*[text word] OR death*[text word] OR burden[text word] OR underreporting[text word] OR “under-reporting”[text word] OR seroprevalence[text word] OR serosurvey[text word] OR serology[text word] OR serology[mesh] OR seroconversion[text word] OR seroconversion[mesh] OR “serosurveillance”[text word] OR Seroepidemiologic studies[mesh] OR seroepid*[text word] OR seropositiv*[text word] OR antibod*[text word] OR

antibodies[mesh] OR surveillance[text word] OR SIR[text word] OR SEIR[text word] OR “susceptible-exposed-infected-removed”[text word] OR “susceptible-infected-removed”[text word]

(1 AND 2 AND 3)

Embase (Elsevier)

Date searched: 7/3/2021
Number of results: 1,119
Date filter: 2020 to 2021
Other filters applied: Embase only and not Medline (as Medline is included in PubMed)

1.
covid-19:ti,ab,kw OR COVID19:ti,ab,kw OR SARS-CoV-2:ti,ab,kw OR SARS-CoV2:ti,ab,kw OR "severe acute respiratory syndrome coronavirus 2":ti,ab,kw OR 2019-nCoV:ti,ab,kw OR 2019nCoV:ti,ab,kw OR coronavirus:ti,ab,kw OR 'Coronavirinae'/exp OR ‘coronavirus disease 2019’/exp

2.
india:ti,ab,kw OR 'india'/exp OR indian:ti,ab,kw OR pakistan:ti,ab,kw OR pakistani:ti,ab,kw OR 'pakistan'/exp OR bangladesh:ti,ab,kw OR bangladeshi:ti,ab,kw OR 'bangladesh'/de OR nepal:ti,ab,kw OR 'nepal'/de OR "sri lanka":ti,ab,kw OR "sri lankan":ti,ab,kw OR 'sri lanka'/de

3.
IFR:ti,ab,kw OR infection*:ti,ab,kw OR CFR:ti,ab,kw OR case*:ti,ab,kw OR transmission*:ti,ab,kw OR mortalit*:ti,ab,kw OR 'mortality'/exp OR fatalit*:ti,ab,kw OR lethalit*:ti,ab,kw OR death*:ti,ab,kw OR burden:ti,ab,kw OR underreporting:ti,ab,kw OR under-reporting:ti,ab,kw OR seroprevalence:ti,ab,kw OR serosurv*:ti,ab,kw OR serology:ti,ab,kw OR 'serology'/exp OR seroconversion:ti,ab,kw OR 'seroconversion'/de OR 'Seroepidemiology'/exp OR seroepid*:ti,ab,kw OR seropositiv*:ti,ab,kw OR antibod*:ti,ab,kw OR 'antibody'/exp OR surveillance:ti,ab,kw OR SIR:ti,ab,kw OR SEIR:ti,ab,kw OR susceptible-exposed-infected-removed:ti,ab,kw OR susceptible-infected-removed:ti,ab,kw

(1 AND 2 AND 3)

isearch (National Library of Medicine)

Date searched: 7/3/2021
Number of results: 1,078
Date filter: January 1, 2020 to [blank]
Other filters applied: filtered to facets bioRxiv, medRxiv, SSRN; searched through title and abstract.

Note: Since isearch is curated to include COVID-19 related studies only, we translated the PubMed concept blocks 2 and 3.

(india OR indian OR pakistan OR pakistani OR bangladesh OR bangladeshi OR nepal OR "sri lanka" OR “sri lankan”) AND (IFR OR infection* OR CFR OR case* OR transmission* OR mortalit* OR fatalit* OR lethalit* OR death* OR burden OR underreporting OR “under-reporting” OR seroprevalence OR serosurvey OR serology OR seroconversion OR “serosurveillance” OR seroepid* OR seropositiv* OR antibod* OR surveillance OR SIR OR SEIR OR “susceptible-exposed-infected-removed” OR “susceptible-infected-removed”)

Global Index Medicus–SEAR & EMR (World Health Organization)

Note: We searched in IMSEAR (Index Medicus for the South-East Asia Region) for India, Bangladesh, Nepal, and Sri Lanka, and we searched in IMEMR (Index Medicus for the Eastern Mediterranean Region) for Pakistan.

For IMSEAR:
Date searched: 7/3/2021
Number of results: 35
Date filter: 2020 to [blank]
Other filters applied: Index filtered to “IMSEAR (South-East Asia)”; searched through title, abstract, subject.

(tw:(covid-19) OR tw:(COVID19) OR tw:(SARS-CoV-2) OR tw:(SARS-CoV2) OR tw:(“severe acute respiratory syndrome coronavirus 2”) OR tw:(2019-nCoV) OR tw:(2019nCoV) OR tw:(coronavirus)) AND (tw:(india) OR tw:(indian) OR tw:(bangladesh) OR tw:(bangladeshi) OR tw:(nepal) OR tw:("sri lanka") OR tw:(“sri lankan”)) AND (tw:(IFR) OR tw:(infection*) OR tw:(CFR) OR tw:(case*) OR tw:(transmission*) OR tw:(mortalit*) OR tw:(fatalit*) OR tw:(lethalit*) OR tw:(death*) OR tw:(burden) OR tw:(underreporting) OR tw:(“under-reporting”) OR tw:(seroprevalence) OR tw:(serosurvey) OR tw:(serology) OR tw:(seroconversion) OR tw:(“serosurveillance”) OR tw:(seroepid*) OR tw:(seropositiv*) OR tw:(antibod*) OR tw:(surveillance) OR tw:(SIR) OR tw:(SEIR) OR tw:(“susceptible-exposed-infected-removed”) OR tw:(“susceptible-infected-removed”))

For IMEMR:
Date searched: 7/3/2021
Number of results: 2
Date filter: 2020 to [blank]
Other filters applied: Index filtered to “IMEMR (Eastern Mediterranean)”; searched through title, abstract, subject.

(tw:(covid-19) OR tw:(COVID19) OR tw:(SARS-CoV-2) OR tw:(SARS-CoV2) OR tw:(“severe acute respiratory syndrome coronavirus 2”) OR tw:(2019-nCoV) OR tw:(2019nCoV) OR tw:(coronavirus)) AND (tw:(pakistan) OR tw:(pakistani)) AND (tw:(IFR) OR tw:(infection*) OR tw:(CFR) OR tw:(case*) OR tw:(transmission*) OR tw:(mortalit*) OR tw:(fatalit*) OR tw:(lethalit*) OR tw:(death*) OR tw:(burden) OR tw:(underreporting) OR tw:(“under-reporting”) OR tw:(seroprevalence) OR tw:(serosurvey) OR tw:(serology) OR tw:(seroconversion) OR tw:(“serosurveillance”) OR tw:(seroepid*) OR tw:(seropositiv*) OR tw:(antibod*) OR tw:(surveillance) OR tw:(SIR) OR tw:(SEIR) OR tw:(“susceptible-exposed-infected-removed”) OR tw:(“susceptible-infected-removed”))

Appendix C. Summary of included articles

Table 1. Summary of data abstraction from included studies.

Location	*Study Design*	*Time Period*	*Age Criteria*	*Sample Size*	*Descriptive Statistics*	*IFR Estimate (95% CI:)[a]*	*Prevalence Estimate % (95% CI:)[a]*	*Reference*
IND–Ahmedabad, Gujarat	cross-sectional serosurvey	Aug 2020	none	N=3973 non-response rate: *N/A*	48.1% female and 51.8% male mean age: 37.5 (± 15.9) years	*N/A*	Overall: 31.92 (30.48–33.38) Age 0–9: 34.69 (21.67–49.64) Age 10–19: 31.66 (27.18–36.51) Age 20–29: 26.63 (23.98–29.47) Age 30–39: 31.98 (29.04–35.08) Age 40–49: 32.58 (29.23–36.12) Age 50–59: 35.55 (31.34–39.99) Age 60–69: 36.10 (30.98–41.56) Age 70–79: 44.72 (35.75–53.94) Age 80–89: 40.91 (20.71–63.65) Age 90–99: 0.00	Prakash, 2021 [2]
IND–Bangalore Rural District of Karnataka	cross-sectional serosurvey	2–22 Oct 2020	age≥18	N=509 non-response rate: *N/A*	47.7% female and 52.3% male mean age: 47.0 (± 16.4) years	0.13% (i.e. 12.8 deaths per 10,000 cases)	*Adjusting for test sensitivity and specificity* Overall: 6.1 (4.02–8.17) *Unadjusted* Overall: 12.4 (9.6–15.6)	Inbaraj, 2021 [3]

							Female: 12.0 (8.8–17.6) Male: 12.0 (8.4–16.6) Age ≤20: 5.6 (0.1–27.3) Age 21–40: 13.6 (8.9–19.5) Age 41–60: 12.5 (8.3–17.8) Age >60: 11.3 (6.0–18.9)	
IND–Bhubaneswar, Berhampur, Rourkela cities of Odisha[1]	cross-sectional serosurvey	Aug 2020	age≥18	N=4146 non-response rate: 27.6% for females 12.4% for males	mean age: 44.2 (± 14.2) years	*N/A*	*Across Three Cities* Overall: 20.30 (19.0–21.56) Female: 22.79 (20.73–24.96) Male: 18.81 (17.33–20.37) Age <20: 17.09 (10.76–25.15) Age 20–29: 18.75 (15.68–22.13) Age 30–39: 21.83 (19.16–24.69) Age 40–49: 19.68 (17.29–22.25) Age 50–59: 18.50 (15.89–21.34) Age ≥60: 23.21 (20.14–26.52)	Kshatri, 2021a [4]
IND–Bhubaneswar, Odisha[1]	serial cross-sectional serosurvey	Jul, Aug, Sept 2020	age≥18	N=3693 non-response rate: 18.33% (across the three rounds)	mean age: 43.1 (± 13.9) years	*N/A*	*Round 1 | Round 2 | Round 3* Overall: 1.58 (0.88–2.58) | 5.23 (4.09–6.57) | 48.61 (45.96–51.26)	Kshatri, 2021b [5]

							Female: 1.29 (0.27–3.72) |5.37 (3.44–7.95) | 50.12 (45.24–54.99) Male: 1.67 (0.87–2.90) | 5.16 (3.80–6.83) | 47.96 (44.79–51.14) Age 18–29: 1.61 (0.33–4.64) | 5.80 (3.35–9.24) | 42.74 (36.31–49.34) Age 30–39: 0.56 (0.01–3.07) | 7.72 (4.96–11.36) | 54.02 (48.30–59.65) Age 40–49: 1.30 (0.27–3.76) | 2.57 (1.12–5.01) | 51.71 (46.75–56.63) Age 50–59: 2.82 (0.92–6.47) | 3.49 (1.61–6.52) | 49.12 (43.15–55.10) Age ≥60: 1.68 (0.35–4.82) | 7.39 (3.99–12.30) | 38.18 (30.73–46.05)	
IND–Chennai, Tamil Nadu	cross-sectional serosurvey	7–14 Jul 2020	age≥10	N=12,405 non-response rate: *N/A* (17.7% not available,13.5% refusal rate)	52.7% female, 47% male, 0.3% transgender mean age: 41.1 (± 17.3) years	*N/A*	*Weighted and test performance adjusted* Overall: 18.4 (14.8–22.6) Female: 20.3 (16.4–25.0) Male: 16.3 (12.9–20.3) Transgender: 2.4 (0.0–27.3) Age 10–19: 18.6 (14.4–23.7) Age 20–29: 20.8 (16.5–25.9)	Selvaraju, 2021 [6]

							Age 30–39: 18.2 (14.3–22.8) Age 40–49: 19.3 (15.2–24.2) Age 50–59: 20.1 (15.8–25.2) Age ≥60: 13.1 (9.9–17.1)	
IND–Chennai, Tamil Nadu	analysis of seroprevalence & mortality data	Jul, Oct, Nov 2020	age≥10 (Jul), age≥ (Oct), age≥18 (Nov)	N=12,405 (Jul), N= (Oct), N=26,135 (Nov) non-response rate: *N/A*	*N/A*	*Adjusting for death undercounting* range: 0.27-0.33% (Jul), 0.30-0.28% (Oct), 0.22-0.25% (Nov) *Not adjusting for death undercounting* range: 0.16-0.20% (Jul), 0.16-0.16% (Oct), 0.13-0.13% (Nov)	*N/A*	Banaji, 2021 [7]
IND–Delhi[2]	cross-sectional serosurvey	15-23 January 2021	age≥5	N=28,000 non-response rate: *N/A*	*N/A*	*N/A*	Overall: 56.1%	*Other*[b] [8]
IND–Delhi	repeated cross-sectional serosurvey	1–7 Aug, 1–7 Sep, 15–21 Oct 2020	age≥5	N=15,046 (Aug); N=17409 (Sep) N=15015 (Oct) non-response rate: 10%	52.5% female and 47.4% male mean age: *N/A*	Aug: 0.77% (0.75–0.79) to 0.79% (0.76–0.81) Sep: 0.98% (0.95–1.01) to 1.03% (1.00–1.06) Oct: 1.27% (1.24–1.31) to 1.34% (1.31–1.38)	*Round 1 | Round 2 | Round 3* Overall: 28.39 (27.65–29.14) | 24.08 (23.43–24.74) | 24.71 (24.01–25.42)	Sharma, 2020 [9]
IND–Delhi[2]	cross-sectional serosurvey	27 Jun–10 July 2020	age≥5	N=21,387 non-response rate: *N/A*	N/A	*N/A*	Overall: 22.86%	*Other*[c] [10]
IND–Delhi[2]	compartmental epidemiologic model	As of 23 Jan 2021	none	*N/A*	*N/A*	*Adjusting for death undercounting* range: 0.4-0.5%	*N/A*	Bhattacharyya, 2021 [11]

IND–Delhi, Mumbai, Pune, Bengaluru, Chennai[2]	compartmental epidemiologic model	1 Mar 2020–15 Feb 2021	none	*N/A*	*N/A*	Bengaluru: 0.05% Chennai: 0.052% Delhi: 0.1% Mumbai: 0.15% Pune: 0.17%	*N/A*	Hazra, 2021 [12]
IND–Delhi urban, Delhi rural, Bhubaneswar rural, Agartala rural, and Gorakhpur rural	prospective serosurvey	15 Mar–10 Jun 2021	age≥2	N=4509 non-response rate: *N/A*	mean age: *N/A* (median age was 11 for Delhi urban, 12 for Delhi rural, 11 for Bhubaneswar, 13 for Gorakhpur, 14 years for Agartala)	*N/A*	Overall: 65.9 (64.6–67.4) Age <18: 59.0 (55.4–62.6) Age ≥18: 67.3 (65.8–68.8 *Rural* Overall: 62.2 (60.7–63.9) Age <18: 55.9 (52.0–59.9) Age ≥18: 63.5 (61.8–65.3) *Urban* Overall: 79.1 (76.5–81.6) Age <18: 78.3 Age ≥18: 79.2	Misra, 2021 [13]
IND–Devarajeevana Halli slum in Bengaluru, Karnataka[1]	cross-sectional serosurvey	Sep 2020	age≥18	N=499 non-response rate: *N/A*	74.3% female and 25.7% male mean age: 39.7 (± 14.5) years	2.94 per 10,000 cases	*Slum* Overall: 57.9 (53.4–62.3) Age ≤20: 52.8 (35.5–69.6) Age 21–40: 57.9 (51.5–64.0) Age 41–60: 59.9 (52.0–67.4) Age >60: 54.8 (38.7–70.2)	George, 2021 [14]
IND–Karnataka	cross-sectional serosurvey	15 Jun–29 Aug 2020	none	N=1408 non-response rate: 34.5%	*N/A*	*N/A*	Overall: 46.7 (43.3–50.0) Rural: 44.1 (40.0–48.2) Urban: 53.8 (48.4–59.2)	Mohanan, 2020 [15]

IND–Karnataka	cross-sectional serosurvey	3–16 Sep 2020	age≥18	N=16,416 non-response rate: *N/A*	48.7% female and 51.2% male mean age: *N/A*	0.05%	Overall: 27.7 (26.1–29.3) Female: 21.9 (19.9–23.8) Male: 29.8 (27.7–31.8) Age 18–29: 19 (16.8–21.3) Age 30–39: 25.7 (22.7–28.7) Age 40–49: 29.3 (25.6–33) Age 50–59: 33.3 (28.9–37.7) Age ≥60: 31.6 (28.1–35)	Babu, 2021 [16]
IND–Karnataka, Mumbai, and among (male) Bihar migrants	matching serosurvey to administrative data	15 Jun–29 Aug 2020 (Karn.) 29 June–19 July 2020 (Mumbai) 4 May–21 July 2020 (Bihar)	age≥10	N=1196 (Karn.) N=6904 (Mumb.) N=4362 (Bihar)	35% female and 65% male mean age: *N/A*	*Karnataka* Male age 10-49: 0.009% (0.007, 0.010) Male age 50-89: 0.120% (0.090, 0.150) Female age 10-49: 0.004% (0.004, 0.005) Female age 50-89: 0.056% (0.043, 0.069) *Mumbai* Male age 10-49: 0.033% (0.032, 0.034) Male age 50-89: 0.530% (0.516, 0.544) Female age 10-49: 0.016% (0.016, 0.017) Female age 50-89: 0.285% (0.277, 0.293)	*N/A*	Cai, 2021 [17]
IND–Kashmir	cross-sectional serosurvey	17 Oct–4 Nov 2020	age≥18	N=6230 non-response rate: *N/*A	49.8% female and 50.2% male mean age: *N/A*	342.1 (320.2–366.0) deaths per million cases	*Weighted and adjusted for test performance* Overall: 36.7 (34.3–39.2) Female: 37.6 (34.3–41.1) Male: 35.9 (33.3–38.7)	Khan, 2021 [18]

							Age 18–29: 33.5 (29.8–37.4) Age 30–49: 36.1 (33.3–39.1) Age 50–69: 42.3 (38.6–46.0) Age ≥70: 45.1 (37.6–52.8) Urban: 40.0 (36.1–43.9) Rural: 35.3 (32.2–38.5)	
IND–Indore, Madhya Pradesh	cross-sectional serosurvey	11–23 Aug 2020	age≥1	N=7103 non-response rate: *N/A*	48.1% female and 51.8% male mean age: *N/A*	1 death per 579 cases	Overall: 7.75 (7.14–8.36) Female: 7.57 (6.70–8.44) Male: 7.91 (7.06–8.76) Age <18: 7.26 (6.24–8.28) Age ≥18: 7.97 (7.21–8.74) Age 18–45: 7.11 (6.22–8.01) Age 45–60: 10.04 (8.28–11.80) Age >60: 8.40 (5.87–10.92)	Sakalle, 2021 [19]
IND–Mumbai, Maharashtra[2]	cross-sectional serosurvey	Mar 2021	*N/A*	N=10,197 non-response rate: *N/A*	*N/A*	*N/A*	Overall: 36.3% Female: 37.12% Male: 35.02% Non-slum: 28.5% Slum: 41.6%	*Other*[d] [19]
IND–Mumbai, Maharashtra	cross-sectional serosurvey	Aug 2020 (last half)	age≥12	N=5200 non-response rate: *N/A*	44.6% female and 55.3% male mean age: *N/A*	*N/A*	*Non-slum* Overall: 17.1% (15.5–18.7) Age 12–24: 18.5% (13.5–23.4)	*Other*[e] [21]

							Age 25–40: 16.6% (13.7–19.5) Age 41–60: 18.6% (16.1–21.0) Age >60: 13.2% (9.6–16.7) *Slum* Overall: 45.3% (43.5–4.70) Age 12–24: 40.8% (37.0–44.6) Age 25–40: 42.4% (39.5–45.3) Age 41–60: 50.3% (47.3–53.3) Age >60: 48.2% (41.7–54.7)	
IND–Mumbai, Maharashtra	cross-sectional serosurvey	29 Jun–19 Jul 2020	age≥12	N=6904 non-response rate: *N/A*	44.6% female and 55.3% male mean age: *N/A*	Overall: 0.12% Slum: 0.076% Non-slum: 0.263%	*Non-slum* Overall: 17.3 (16.0–18.7) Matunga: 19.2 (17.0–21.4) Chembur West: 17.9 (15.6–20.3) Dahisar: 12.8 (10.2–15.4) *Slum* Overall: 58.4 (56.8–59.9) Matunga: 61.7 (59.6–63.8) Chembur West: 59.4 (57.0–61.8) Dahisar: 54.9 (50.7–59.1)	Malani, 2020 [22]

IND–Mumbai, Maharashtra	analysis of seroprevalence & mortality data	29 Jun–19 Jul 2020	age≥12	N=6904 non-response rate: *N/A*	44.6% female and 55.3% male mean age: *N/A*	*Adjusting for death undercounting* Overall: 0.23% (0.15–0.33) *Not adjusting for death undercounting* Slum: 0.084% (0.068–0.10) Non-slum: 0.29% (0.22–0.38)	*N/A*	Banaji, 2021 [23]
IND–nationwide	Fourth cross-sectional survey	14 June–6 July 2021	age≥6	N=28,975 non-response rate: *N/A*	*N/A*	*N/A*	Overall: 67.6% (66.4–68.7) Female: 69.2% (67.9–70.5) Male: 65.8% (64.4–67.1) Age 6–9: 57.2% (55.0–59.4) Age 10–17: 61.6% (59.8–63.3) Age 18–44: 66.7% (65.3–68.0) Age 45–60: 77.6% (76.1–79.0 Age >60: 76.7% (74.6–78.7) Rural: 66.7% (65.4–68.1) Urban: 69.6% (67.5–71.7)	*Other*[f] [24]
IND–nationwide	Third cross-sectional survey	18 Dec 2020–6 Jan 2021	age≥10	N=28,598 non-response rate: *N/A*	51.6% female and 48.4% male mean age: 38.2 (± 16.4) years	*N/A*	Overall: 24.1 (23.0–25.3) Female: 24.9 (23.7–26.3) Male: 23.2 (22.1–24.5) Age 10–17: 27.2 (24.9–29.4) Age 18–44: 22.2 (21.1–23.4)	Murhekar, 2021 [25]

							Age 45–60: 26.7 (25.2–28.2) Age >60: 26.3 (24.3–28.3) Rural: 21.4 (20.3–22.6) Urban non-slum: 29.5 (27.0–32.1) Urban slum: 34.7 (31.2–38.5)	
IND–nationwide	Second cross-sectional survey	18 Aug–20 Sep 2020	age≥10	N=29,082 non-response rate: 17%	48.8% female and 51.2% male mean age: 37.0 (± 16.4) years	0.09–0.11% 9.43 (8.41–10.73) to 10.65 (9.50–12.12) deaths per 10,000 cases	Overall: 6.6 (5.8–7.4) Female: 6.5 (5.7–7.3) Male: 6.7 (5.9–7.5) Age 10–17: 5.4 (4.5–6.4) Age 18–44: 6.9 (6.1–7.7) Age 45–60: 6.5 (5.7–7.5) Age >60: 6.2 (5.2–7.3) Rural: 5.2 (4.6–6.0) Urban non–slum: 9.0 (7.1–11.3) Urban slum: 16.9 (12.9–21.7) *Randomly generated sample* Overall: 7.1 (6.2–8.2)	Murhekar, 2021 [26]
IND–nationwide	First cross-sectional survey	11 May–4 Jun 2020	age≥18	N=28,000 non-response rate: N/A (86.9-95.9% across strata)	51.5% female and 48.4% male mean age: 45.3 (± 15.2) years	11.72 (7.21–19.19) to 15.04 (9.26–24.62) deaths per 10,000 cases	Overall: 0.73 (0.34–1.13)	Murhekar, 2020 [27]
IND–nationwide	analysis of seroprevalence	31 Mar 2020	none	*N/A*	*N/A*	0.41%	*N/A*	Bommer, 2020 [27]

	& mortality data							
IND–nationwide IND– Andhra Pradesh, Assam, Bihar, Delhi, Goa, Gujarat, Haryana, Jharkhand, Karnataka, Kerala, Madhya Pradesh, Maharashtra, Odisha, Punjab, Rajasthan, Tamil Nadu, Telangana, Uttarakhand, West Bengal	compartmental epidemiologic model	*Wave 1* 1 Apr 2020-31 Jan 2021 *Wave 2* 1 Feb-15 May 2021	none	*N/A*	*N/A*	IFR1 | IFR2 *Wave 1* India: 0.129% (0.125–0.134) | 0.461% (0.455–0.468) Maharashtra: 0.460 (0.444-0.480) | 0.968 (0.955-0.985) Punjab: 0.362 (0.331-0.397) | 1.010 (0.991-1.031) West Bengal: 0.322 (0.289-0.357) | 0.675 (0.665-0.686) Gujarat: 0.284 (0.267-0.302) | 0.592 (0.579-0.606) Tamil Nadu: 0.226 (0.210-0.243) | 0.514 (0.504-0.523) Karnataka: 0.207 (0.199-0.216) | 0.505 (0.499-0.511) Rajasthan: 0.168 (0.153-0.186) | 0.428 (0.415-0.443) Madhya Pradesh: 0.163 (0.154-0.173) | 0.328 (0.319-0.338) Haryana: 0.148 (0.131-0.172) | 0.428 (0.411-0.453) Odisha: 0.137 (0.117-0.160) | 0.351 (0.333-0.367)	*N/A*	Purkayastha, 2021 [29]

	Jharkhand: 0.122 (0.094-0.156) | 0.238 (0.226-0.252) Telangana: 0.099 (0.065-0.165) | 0.261 (0.250-0.273) Bihar: 0.086 (0.073-0.103) | 0.204 (0.191-0.219) Uttarakhand: 0.078 (0.062-0.104) | 0.404 (0.390-0.426) Assam: 0.069 (0.060-0.081) | 0.168 (0.160-0.177) Kerala: 0.061 (0.057-0.067) | 0.144 (0.140-0.148) Delhi: 0.060 (0.060-0.061) | 0.380 (0.377-0.383) Goa: 0.051 (0.049-0.053) | 0.320 (0.311-0.329) Andhra Pradesh: 0.019 (0.019-0.019) | 0.168 (0.167-0.170) *Wave 2* India, wave 2: 0.032 (0.029–0.035) | 0.183 (0.180–0.186) India, across waves 1 and 2: 0.06 | 0.24 Goa: 0.102 (0.101-0.103) | 0.393 (0.382-0.405) Delhi: 0.081 (0.080-0.081) | 0.298 (0.295-0.301) Punjab: 0.049 (0.045-0.056) | 0.397 (0.390-0.404) Assam: 0.047 (0.037-0.065) | 0.221 (0.209-0.240)

	Maharashtra: 0.047 (0.046-0.049) | 0.209 (0.207-0.211) Uttarakhand: 0.045 (0.044-0.048) | 0.387 (0.381-0.393) Uttar Pradesh: 0.026 (0.023-0.030) | 0.166 (0.163-0.170) Rajasthan: 0.024 (0.019-0.029) | 0.173 (0.168-0.179) Karnataka: 0.022 (0.022-0.023) | 0.201 (0.199-0.203) West Bengal: 0.022 (0.019-0.026) | 0.105 (0.102-0.109) Tamil Nadu: 0.021 (0.020-0.022) |0.131 (0.130-0.133) Gujarat: 0.020 (0.017-0.023) | 0.188 (0.185-0.192) Haryana: 0.019 (0.019-0.020) | 0.159 (0.157-0.161) Jharkhand: 0.017 (0.016-0.018) | 0.311 (0.308-0.314) Madhya Pradesh: 0.015 (0.013-0.016) | 0.132 (0.130-0.134) Andhra Pradesh: 0.013 (0.012-0.014) | 0.093 (0.091-0.095) Kerala: 0.012 (0.012-0.012) | 0.056 (0.055-0.056)

						Telangana: 0.011 (0.009-0.013) | 0.110 (0.108-0.113) Bihar: 0.005 (0.005-0.006) | 0.103 (0.102-0.105) Odisha: 0.002 (0.002-0.002) | 0.028 (0.028-0.029)		
IND–nationwide IND–Delhi	Bayesian model with seroprevalence & mortality data	11 May –4 Jun 2020 (overall India) 1–7 August 2020 (Delhi)	age≥18 for overall India age≥5 for Delhi	28,000 (India) N=15,046 (Delhi); non-response rate: N/A (India); 10% (Delhi)	51.5% female and 48.4% male (India) 52.5% female and 47.4% male (Delhi); mean age: 45.3 (SD 15.2) years (India); N/A (Delhi)	*Adjusting for death undercounting:* For overall India: 0.29% (0.06–0.58) For Delhi: 0.17% (0.07–0.40)	*For overall India* 0.7% (0.4–1.1) *For Delhi* 28.4% (27.6–29.1)	Campbell, 2021 [30]
IND–nationwide IND–Delhi, Maharashtra[2]	compartmental epidemiologic model	As of 1 Sep 2020	none	*N/A*	*N/A*	*Adjusting for death undercounting* India: 0.91% Delhi: 0.91% Maharashtra: 1.24%	*N/A*	Bhaduri, 2020 [31]
IND–Pimpri-Chinchiwad, Maharashtra[1]	cross-sectional survey	7–17 Oct 2020	age≥12	N=5000 non-response rate: 10%	*N/A*	0.17%	Overall: 34.04 (31.3–36.8) Female: 36.6 (33.7–39.5) Male: 31.0 (28.0–34.1) Age 12–17: 37.6 (31.2–44.0) Age 18–30: 31.9 (28.8–35.0) Age 31–50: 33.8 (30.3–37.3) Age 51–65: 38.2 (33.6–42.9)	Banerjee, 2020 [32]

							Age >65: 30.6 (24.4–36.8) Slum: 40.9 (37.0–44.7) Tenement: 41.2 (37.7–44.8) Housing: 29.8 (25.8–33.8)	
IND–nationwide IND– Andhra Pradesh, Delhi, Gujarat, Haryana, Jammu & Kashmir, Karnataka, Kerala, Madhya Pradesh, Maharashtra, Rajasthan, Tamil Nadu, Telangana, Uttar Pradesh	analysis of IFRs, fatality and testing data	Through 8 Apr 2020	none	*N/A*	*N/A*	*Adjusting for death undercounting* India: Andhra Pradesh: Delhi: 0.396% Gujarat: 0.437% Haryana: 0.394% Jammu & Kashmir: 0.358% Karnataka: 0.440% Kerala: 0.579% Madhya Pradesh: 0.364% Maharashtra: 0.435% Rajasthan: 0.358% Tamil Nadu: 0.524% Telangana: 0.432% Uttar Pradesh: 0.335%	*N/A*	Goli, 2020 [33]
IND–Puducherry	serial three-phase cross-sectional serosurvey	11–16 Aug, 10–16 Sep, 12–16 Oct 2020	age≥18	N=2667 (869 in Phase 1, 898 in Phase 2, 900 in Phase 3) non-response rate: 2.2%	mean age: *N/A* (median age in mid-40's)	*Phase 1 | Phase 2 | Phase 3* 73.4 deaths per 100,000 infected persons | 75.8 deaths per 100,000 infected persons | 106.1 deaths per 100,000 infected persons	*Phase 1| Phase 2|Phase 3* Overall: 4.9 (3.5–6.4) | 20.7 (18.0–23.3) | 34.5 (31.5–37.7) Female: 6.3 (4.0–8.6) | 20.0 (16.3–23.6) | 37.2 (33.1–41.6) Male: 3.6 (1.9–5.4) | 21.4 (17.6–25.2) | 31.0 (26.7–35.6)	Kar, 2021 [34]

							Age 18–29: 4.7 (1.5–7.8) | 20.0 (13.9–26.1) | 32.2 (25.8–39.3) Age 30–44: 4.4 (2.1–6.7) | 20.9 (16.2–25.7) | 36.5 (30.8–42.6) Age 45–59: 5.4 (2.5–8.2) | 23.6 (18.5–28.7) | 39.0 (33.2–45.0) Age ≥60: 5.6 (2.0–9.1) | 16.7 (11.4–22.1) | 28.7 (23.0–35.1) Rural: 3.1 (1.0–5.2) | 20.8 (16.0–25.7) | 31.6 (26.3–37.4) Urban: 5.7 (3.9–7.5) | 20.7 (17.5–23.8) | 35.8 (32.1–39.7)	
IND–Tamil Nadu	cross-sectional survey	19 Oct–30 Nov 2020	age≥18	N=26,135 non-response rate: *N/A*	61% female and 39% male mean age: *N/A*	Female age 18–29: 0.002% Female age 30–39: 0.006% Female age 40–49: 0.019% Female age 50–59: 0.060% Female age 60–69: 0.143% Female age ≥70: 0.266% Male age 18–29: 0.003% Male age 30–39: 0.015% Male age 40–49: 0.045% Male age 50–59: 0.164% Male age 60–69: 0.380% Male age ≥70: 0.923%	Overall: 31.6 (30.4–32.8) Female: 32.1 (31.1–33.0) Male: 30.4 (29.6–31.2) Age 18–29: 31.1 (30.3–31.8) Age 30–39: 32.0 (31.2–32.7) Age 40–49: 33.3 (32.5–34.0) Age 50–59: 33.2 (32.4–33.9) Age 60–69: 28.4 (27.7–29.1) Age ≥70: 25.2 (24.5–25.8)	Malani, 2021 [35]

							Rural: 25.1 (24.2–26.1) Urban: 36.7 (35.7–37.7)	
IND–Ujjain, Madhya Pradesh	cross-sectional survey	24 Aug–5 Sep 2020	age≥1	N=4883 non-response rate: *N/A*	56.3% female and 43.7% male mean age: *N/A*	*N/A*	Overall: 13.9 (10.4–18.0) Female: 11.7 Male: 16.5 Age <15: 9.5 Age 15–30: 12.2 Age 30–45: 17.1 Age 45–60: 16.7 Age >60: 10.8	Joshi, 2021 [36]
PAK–District East and District Malir in Karachi[3]	serial three-round cross-sectional serosurvey	15–25 Apr, 25 Jun–11 Jul, 17–22 Aug 2020	none	N=3005 non-response rate: *N/A* (refusal rates 68%, 43%, 61% for DE; 44%, 42%, 8% for DM)	mean age: 25.9–27.1 for District East and 24.32–28.5 for District Malir	*Phase 1*| *Phase 2* | *Phase 3* 1.66% | 0.37% | 0.26%	*Phase 1*| *Phase 2*|*Phase 3* *District East* Overall: 0.4 (0.0–1.3) | 15.1 (9.4–21.7) | 21.5 (15.6–28) *District Malir* Overall: 0.2 (0.0-0.7) | 8.7 (5.1–13.1) | 12.8 (8.3–17.7)	Nisar, 2021 [37]
PAK–Khyber Pakhtunkhwa Sindh, Punjab[3]	cross-sectional serosurvey	15–31 Jul 2020	none	N=15,390 non-response rate: *N/A*	20.2% female and 79.8% male mean age: 35.2 (± 13.2) years	*N/A*	*Across provinces* Overall: 42.4 (41.5–43.14) Female: 40.5 (38.7–42.2) Male: 42.8 (41.9–43.7) Age ≤20: 36.7 (34.2–39.1) Age 21–40: 42.3 (41.3–43.3) Age 41–60: 44.3 (42.7–45.9)	Haq, 2021 [38]

											Age >60: 44.6 (40.7–48.5) *Khyber Pakhtunkhwa* Overall: 42.2 (41.2–44.0) *Sindh* Overall: 31.8 (29.6–34.1) *Punjab* Overall: 44.5 (43.5–45.6)

Note: Entries are in alphabetical order by location of study and in descending order by study start date. N/A = Not Available. Studies highlighted in grey have been included in the quantitative analysis.

[1] No reported death or case counts are available for the city or slum from *covid19india.org*, at the time of this review.

[2] No 95% confidence intervals (CI) or 95% credible intervals were provided in the underlying study for either IFR or seroprevalence estimate.

[3] Location of the study is outside of India and the meta-analysis focuses on India.

[a] The 95% confidence intervals (CI) or 95% credible intervals presented in this table are directly reported from each underlying study, if provided.

[b] Data from media reports. (Hindustan Times 2021: Available at: https://www.hindustantimes.com/cities/delhi-news/a-look-at-serological-surveys-conducted-in-delhi101612270983224.html)

[c] Data from media reports. (The Hindu. Published online July 22, 2020. Available at: https://www.thehindu.com/news/cities/Delhi/percentage-of-people-with-antibodies-high/article32156162.ece)

[d] Data collected from technical report. (Available at: https://www.tifr.res.in/TSN/article/Mumbai-Serosurvey%20Technical%20report-NITI_BMC-Round-2%20for%20TIFR%20website.pdf)

[e] Data from media reports. (The Hindu. Published on April 25, 2021. Available at: https://www.thehindu.com/news/cities/mumbai/third-sero-survey-antibodies-in-3630-samples-in-mumbai/article34404107.ece)

[f] Data from media reports. (Press Information Bureau, National Media Center. Briefing on COVID-19. Published on July 20, 2021)

Appendix D. List of excluded articles

Table 1. List of excluded articles from qualitative review and reason for exclusion.

First Author, Ref	Location (Country–Location)	Reason for Exclusion
Ahamad, [39]	Bangladesh	Provides no relevant seroprevalence or IFR
Ahamad, [40]	Bangladesh	Provides no relevant seroprevalence or IFR
Al-Bari, [41]	Bangladesh	Provides no relevant seroprevalence or IFR
Barnwal, [42]	Bangladesh	Provides no relevant seroprevalence or IFR
Dey, [43]	Bangladesh	Provides no relevant seroprevalence or IFR
Hasan, [44]	Bangladesh	Active recruitment of participants
Islam, [45]	Bangladesh	Provides no relevant seroprevalence or IFR
Islam, [46]	Bangladesh	Provides no relevant seroprevalence or IFR
Khan, [47]	Bangladesh	Provides no relevant seroprevalence or IFR
Mukaddes, [48]	Bangladesh	Provides no relevant seroprevalence or IFR
Rahman, [49]	Bangladesh	Provides no relevant seroprevalence or IFR
Siam, [50]	Bangladesh	Provides no relevant seroprevalence or IFR
Russell, [51]	Bangladesh and others	Provides forecasted estimates
Rana, [52]	Bangladesh–Southern Bangladesh	Focuses on asymptomatic individuals
Adapa, [53]	India	Provides no relevant seroprevalence or IFR
Adapa, [54]	India	Provides no relevant seroprevalence or IFR
Al Arydah, [55]	India	Provides no relevant seroprevalence or IFR
Asirvatham, [56]	India	Provides no relevant seroprevalence or IFR
Cai, [57]	India	Previous version
Chatterjee, [58]	India	Provides no relevant seroprevalence or IFR
Chatterjee, [59]	India	Provides forecasted estimates
Frost, [60]	India	Provides forecasted estimates
Gonzalez, [61]	India	Provides no relevant seroprevalence or IFR
Gupta, [62]	India	Focuses on tested individuals
Gupta, [63]	India	Provides no relevant seroprevalence or IFR
Jahan, [64]	India	Provides no relevant seroprevalence or IFR
Kumar, [65]	India	Provides no relevant seroprevalence or IFR
Kumar, [66]	India	Provides no relevant seroprevalence or IFR
Menon, [67]	India	Provides no relevant seroprevalence or IFR
Mohanty, [68]	India	Provides no relevant seroprevalence or IFR
Mukhopadhyay, [69]	India	Provides no relevant seroprevalence or IFR
Naushin, [70]	India	Focuses on laboratory workers
Neve, [71]	India	Provides forecasted estimates
Parai, [72]	India	Focuses on healthcare workers
Radha, [73]	India	Provides no relevant seroprevalence or IFR
Ranjan, [74]	India	Provides no relevant seroprevalence or IFR

Jayesh, [75]	India	Provides no relevant seroprevalence or IFR
Singh, [76]	India	Focuses on high contact workers
Srivastav, [77]	India	Provides no relevant seroprevalence or IFR
Tamrakar, [78]	India	Provides no relevant seroprevalence or IFR
Unnikrishnan, [79]	India	Provides no relevant seroprevalence or IFR
Venkatesan, [80]	India	Conducted at a hospital/healthcare clinic/ICU
Wang, [81]	India	Provides forecasted estimates
Yadav, [82]	India	Focuses on patient cohort
Ansari, [83]	India	Provides no relevant seroprevalence or IFR
Abraham, [84]	India	Provides no relevant seroprevalence or IFR
Giri, [85]	India and hotspot regions	Provides no relevant seroprevalence or IFR
Shah, [86]	India and others	Provides no relevant seroprevalence or IFR
Wong, [87]	India and others	Examines pediatric participants
Zaveri, [88]	India and others	Provides no relevant seroprevalence or IFR
Bhattacharyya, [89]	India and states	Previous version
Chauhan, [90]	India and states	Provides no relevant seroprevalence or IFR
Meghana, [91]	India and states	Provides forecasted estimates
Mukherjee, [92]	India and states	Previous version
Purkayastha, [93]	India and states	Previous version
Patel, [94]	India, Bangladesh, and Pakistan	Provides no relevant seroprevalence or IFR
Velumani, [95]	India–12 cities across India	Focuses on tested individuals
Gupta, [96]	India–52 districts and 20 states across India	Focuses on SARI patient cohort
Prakash, [97]	India–Ahmedabad, Gujarat	Focuses on healthcare workers
Mahto, [98]	India–Bihar	Focuses on healthcare workers
Malani, [99]	India–Bihar	Focuses on working individuals
Madhusudan, [100]	India–Chennai, Tamil Nadu	Focuses on healthcare workers
Pons Salort, [101]	India–Delhi	Provides forecasted estimates
Siddiqui, [102]	India–Delhi	Conducted at a hospital/healthcare clinic/ICU
Thiruvengadam, [103]	India–Delhi	Focuses on patient cohort
Kaushal, [104]	India–Dharavi Slum in Mumbai, Maharashtra	Provides no relevant seroprevalence or IFR
Mishra, [105]	India–Eastern India	Focuses on healthcare workers
Kataria, [106]	India–Gurugram, Haryana	Focuses on healthcare workers
Ranjan, [107]	India–Karnataka	Provides no relevant seroprevalence or IFR
Khan, [108]	India–Kashmir	Focuses on healthcare workers
Kumar, [109]	India–Kerala	Focuses on healthcare workers
Kaur, [110]	India–Majha, Punjab	Focuses on patient cohort
Goenka, [111]	India–metropolitan city	Focuses on healthcare workers
Kumar, [112]	India–Mumbai, Maharashtra	Focuses on healthcare workers

Mahajan, [113]	India–Mumbai, Maharashtra	Focuses on healthcare workers
Mahajan, [114]	India–Mumbai, Maharashtra	Focuses on healthcare workers
Singhal, [115]	India–Mumbai, Maharashtra	Focuses on healthcare workers
Tanna, [116]	India–Nagpur, Maharashtra	Focuses on patient cohort
Sharma, [117]	India–New Delhi	Focuses on healthcare workers
Gupta, [118]	India–Northern India	Focuses on healthcare workers
Khan, [119, p. 2]	India–District Srinagar	Focuses on patient cohort
Satpati, [120]	India–Paschim Medinipur, West Bengal	Focuses on asymptomatic individuals
Mahto, [121]	India–Patna, Bihar	Focuses on healthcare workers
Bogam, [122]	India–Pune, Maharashtra	Provides no relevant seroprevalence or IFR
Ghose, [123]	India–Pune, Maharashtra	Focuses on asymptomatic individuals and high incidence sub-wards
Monteiro, [124]	India–Pune, Maharashtra	Provides no relevant seroprevalence or IFR
Sharma, [125]	India–Punjab	Provides no relevant seroprevalence or IFR
Vignesh, [126]	India–Tamil Nadu	Provides no relevant seroprevalence or IFR
Laxminarayan, [127]	India–Tamil Nadu and Andhra Pradesh	Provides no relevant seroprevalence or IFR
Panchamia, [128]	India–three states in Western India	Focuses on elderly homes
Suresh, [129]	India–Uttar Pradesh	Conducted at a hospital/healthcare clinic/ICU
Banerjee, [130]	India–West Bengal	Conducted at a hospital/healthcare clinic/ICU
Basnet, [131]	Nepal	Provides no relevant seroprevalence or IFR
Dhimal, [132]	Nepal	Provides no relevant seroprevalence or IFR
Pathak, [133]	Nepal	Provides no relevant seroprevalence or IFR
Sharma, [134]	Nepal	Conducted at a hospital/healthcare clinic/ICU
Abbas, [135]	Pakistan	Focuses on healthcare workers
Chaudhry, [136]	Pakistan	Provides no relevant seroprevalence or IFR
Din, [137, p. 19]	Pakistan	Provides no relevant seroprevalence or IFR
Peter, [138]	Pakistan	Provides forecasted estimates
Waqar, [139]	Pakistan	Focuses on symptomatic individuals
Zaidi, [140]	Pakistan	Focuses on working individuals
Naiyar, [141]	Pakistan–Gujrat, Punjab	Conducted at a hospital/healthcare clinic/ICU
Younas, [142]	Pakistan–Karachi, Sindh	Conducted among blood donors
Ali, [143]	Pakistan–Khyber Pakhtunkhwa	Focuses on patient cohort
Haq, [144]	Pakistan–Khyber Pakhtunkhwa	Focuses on healthcare workers
Javed, [145]	Pakistan–multiple cities across Pakistan	Focuses on working individuals
Nisar, [146, p. 2]	Pakistan–Peshawar	Conducted among blood donors
Jeewandara, [147]	Sri Lanka–Colombo, Western Province	Focuses on asymptomatic individuals

Appendix E. Summary of excluded articles

Table 1. Summary of excluded articles by country, type of study, and reason

Exclusion Reason[a]	***Type of Study***	***Number of Excluded Studies***				
		India	***Bangladesh***	***Nepal***	***Pakistan***	***Sri Lanka***
Hospital, urgent or tertiary care	Serosurvey	6	--	--	2	--
	Other	6	--	1	--	--
Healthcare workers	Serosurvey	16	--	--	2	--
	Other	--	--	--	--	--
Workers[b]	Serosurvey	1	--	--	2	--
	Other	1	--	--	--	--
Asymptomatic or Symptomatic	Serosurvey	2	1	--	1	1
	Other	--	--	--	--	--
Blood donors	Serosurvey	--	--	--	2	--
	Other	--	--	--	--	--
Testing center	Serosurvey	1	--	--	--	--
	Other	1	--	--	--	--
Active recruitment	Serosurvey	--	--	--	--	--
	Other	--	1	--	--	--
Elderly care persons	Serosurvey	--	--	--	--	--
	Other	1	--	--	--	--
No relevant measures	Serosurvey	--	--	--	--	--
	Other	43	13	3	4	--
Total Excluded Studies[c]:		***78***	***15***	***4***	***13***	***1***

(a) Studies excluded in the full-text screening are included in this table.

(b) Study population is limited to one or more working occupations (e.g., industrial workers, street vendors, industrial workers and street vendors, etc.).

(c) The summation of *Total Excluded Studies* across countries does not equal 109 studies because there are studies that examine multiple of the focus countries (e.g., India and Bangladesh, etc.). Phrased otherwise, the column counts in this table are not mutually exclusive.

Appendix F. Meta-analysis methodology

The aims of the meta-analysis are two-fold (1) estimate a nationwide IFR_1 and IFR_2 with lower and upper bounds based on nationwide excess deaths, and (2) estimate regional IFR_1 and IFR_2 with lower and upper bounds based on state/city/district-specific excess deaths.

Data collection and preparation

A description of the data collection and preparation of the datafile for the meta-analysis is provided in the ***Methods*** section. Here we elaborate on aspects that require further explanation and clarification.

For included studies with a pre-calculated infection fatality rate, the IFR_1 and/or IFR_2, along with the 95% confidence interval, are directly extracted from the included study. For studies that provide a pre-calculated IFR_1 but no IFR_2 (i.e., do not further account for death underreporting), we compute the IFR_2 through multiplying the numerator of the pre-calculated IFR_1 by the appropriate range of excess deaths estimates. For studies that report a pre-calculated IFR_2 but no IFR_1 (i.e., do not provide preliminary infection fatality estimate without accounting for death reporting), we compute the IFR_1, using the seroprevalence estimate quoted within the included study and following the same steps described below to compute IFR_1.

For studies without a pre-calculated IFR_1 and/or IFR_2, IFR_1 and/or IFR_2 is computed, as given in the below formulas

$$IFR_1 = \frac{Reported\ Cumulative\ Deaths}{\boldsymbol{Estimated}\ Total\ Cumulative\ Infections} \qquad (a)$$

$$IFR_2 = \frac{\boldsymbol{Estimated}\ Total\ Cumulative\ \ Deaths}{\boldsymbol{Estimated}\ Total\ Cumulative\ \ Infections} \qquad (b)$$

where

$$\boldsymbol{Estimated}\ Total\ Cumulative\ \ Infections = Seroprevalence * Age\ Adjusted\ Population$$

and

$$\boldsymbol{Estimated}\ Total\ Cumulative\ \ Deaths = Reported\ Cumulative\ Deaths * Death\ Underreporting\ Factor.$$

For the denominator in formulas (a) and (b), the seroprevalence estimate corresponding to the general study population, as well as the 95% confidence interval, are directly extracted from the included study. We retrieved seroprevalence estimates that were adjusted (within the serosurvey design) for the test performance and weighted to be representative of the study's general population (typically, for the demographics age and sex, among others, such as rural versus urban), if available. For studies that did not both weight and account for test

performance, we extracted the solely weighted or solely test performance adjusted seroprevalence estimate, as provided. For studies that did not report either a weighted or a test performance adjusted seroprevalence estimate, we retrieved the provided crude seroprevalence estimates. The age-adjusted population estimate is calculated as the 2019 projected population estimate on the 2011 census website multiplied by the proportion of the population above the age-cutoff of the included study (e.g., proportion of the population of Karnataka aged ≥ 18 years), as obtained from the age composition for the study area from the 2011 census. As noted in the ***Results*** section, for select cities and districts, no 2019 projected population estimate was available and as such we use the 2011 census population estimates for the following cities and districts: Ahmedabad, Chennai, Bangalore Rural District, Indore, Ujjain. We note that this may lead to an overestimation of IFR_1 nor IFR_2 from these studies, and in turn slightly inflated pooled estimates for the regions containing these study locations.

For the numerator in formulas (a) and (b), COVID-19 reported cumulative deaths are sourced from *covid19india.org* and collected 14 days after the study end date to account for delay in death from SARS-CoV-2 symptom onset. In practice, reported (i.e., observed) deaths for the target population are obtained some specified number of days after the end date of the serological study that varies between studies (e.g., from 2 days [35] to 21 days [14] [18], among others). Levin et al., 2021 [148] perform a simulation-based sensitivity analysis to derive an appropriate fatality delay, and propose and adopt in their systematic review of age-specific infection fatality rates a fatality delay of 4 weeks after the midpoint of the serosurvey. As previously discussed, reported deaths were not available for select cities or districts in *covid19india.org* and so we were not able to compute IFR_1 nor IFR_2 for the cities or districts-level studies Berhampur, Bhubaneswar, Pimpri-Chinchiwad, Rourkela and Devarajeevana Halli slum in Bengaluru, and thereby were not able to include these studies in the quantitative meta-analysis (as listed in ***Appendix G***).

For the numerator in formula (b), the death under reporting factor is either directly extracted from media reports and excess deaths studies available at the time of this report (as are listed in the ***Methods*** section) or calculated using excess cumulative deaths estimates provided within these sources. For the latter, URF (D) is computed as the provided excess deaths estimate divided by the COVID-19 reported deaths 14 days after the end date of the study end date, as previously reasoned. As previously noted, excess deaths were not available for the following states at the time of this study and so we were unable to compute IFR_2, as well as include in the regional analysis, the following states and corresponding studies: Jammu and Kashmir (ref) and Puducherry (ref).

Being that the infection fatality rate (IFR) measure is understood to be a rate and that upon inspection its distribution was heavily right skewed, a log transformation is applied to the sampling data to approximate a normal distribution.

For the 95% confidence interval for IFR_1, first we obtain the standard error for seroprevalence from the directly provided 95% confidence interval from each included study as

$$se_{sero} = \frac{Upper-Lower}{1.96*2} = \frac{Upper-Lower}{3.92} \qquad (c)$$

Now that we have the standard error for seroprevalence, the standard error for the log of IFR_1 can be obtained as IFR_1 relies on $Seroprevalence$ as detailed in formula (a) above. First, notice that

$$log(IFR_1) = log\left\{\frac{Reported\ Deaths}{Total\ Cumulative\ Infections}\right\}$$

By rules of logarithmic operations, it follows that

$$= log(Reported\ Deaths) - log(Total\ Cumulative\ Infections)$$

By the definition in formula (a) and assuming $Reported\ Deaths$ do not contribute to variability and are thereby fixed, it follows that

$$= C - log(n * \hat{p}_{sero})$$

where n is the study sample size and $\hat{p}_{sero}$ is the seroprevalence estimate from the included study.

By rules of logarithmic operations, we have that

$$= C - log(n) - log(\hat{p}_{sero})$$

Assuming n does not contribute to variability and fixing at some constant

$$= C^* - log(\hat{p}_{sero})$$

Therefore, $log(IFR_1) = C^* - log(\hat{p}_{sero})$. Let us consider the variance of $log(IFR_1)$.

Substituting in for $log(IFR_1)$ from above, we have

$$Var(log\, IFR_1) = Var(log\, \hat{p}_{sero})$$

From the Taylor Series expansion, it follows that

$$Var(log\, \hat{p}_{sero}) \approx \frac{1}{\hat{p}_{sero}^2} Var(\hat{p}_{sero})$$

Then, the standard error for the log of IFR_1 is given by

$$se_{IFR_1} \approx \frac{1}{\hat{p}_{sero}} * se_{sero}$$

where se_{sero} is defined as in formula (c) above and $\hat{p}_{sero}$ is the directly provided seroprevalence estimate.

Then, letting $\hat{\theta}$ denote the estimate of $log\ IFR_1$, the asymptotic approximate 95% confidence interval for $log\ IFR_1$ is as follows:

$$(\hat{\theta} - 1.96 * se_{IFR1}, \hat{\theta} + 1.96 * se_{IFR1})$$

The resulting confidence intervals are then exponentiated to back-transform from the logarithmic scale.

For the 95% confidence interval for IFR_2, as the upper and lower bounds of the 95% confidence interval for the associated $URF\ (D)$ are often not available (i.e., the range of uncertainty associated with excess deaths estimates is not consistently available), the asymptotic approximate 95% confidence interval for IFR_2 is obtained by multiplying the 95% confidence interval for IFR_1 by the associated $URF\ (D)$.

Meta-analysis framework

A random effects model is used with the DerSimonian-Laird (DL) estimator for τ^2 (also denoted as tau^2), the variance of the true effect sizes. The DL estimator, $\widehat{\tau^2_{DL}}$, is given by

$$\widehat{\tau^2_{DL}} = \max\left\{0, \frac{Q_w - (k-1)}{\left[\sum_i w_i - \left(\frac{\sum_i {w_i}^2}{\sum_i w_i}\right)\right]}\right\} \qquad (e)$$

where Q_w denotes the appropriate test statistic with $k\text{-}1$ denoting the degrees of freedom and w_i denotes the sampling weight for the i^{th} included study datapoint.

The inverse variance approach is then used to obtain the pooled estimates (nationwide, regional, and state-specific within India). This means that the weighting in the random effects model is the inverse of the sampling variance, as follows

$$w_i^{\{DL\}} = \frac{1}{se_i^2 + \widehat{\tau^2_{DL}}} \qquad (f)$$

where i denotes the i^{th} included study datapoint, se_i^2 is the standard error from the i^{th} included study estimate, and $\widehat{\tau^2_{DL}}$ is the DL estimated random effects variance component, as defined in (e) above.

Using a random effects model with inverse variance method and DL estimator, the estimate for the pooled effect size is then given as follows:

$$\hat{\theta} = \frac{\sum_i \hat{\theta}_i w_i^{\{DL\}}}{\sum_i w_i^{\{DL\}}} \qquad (e)$$

As previously mentioned, a log transformation is applied to the sampling data to approximate a normal distribution. In other words, we log transform both IFR_1 and IFR_2 in the meta-analysis and appropriately back-transform the resulting point estimates and standard errors by exponentiating the log-transformed values. Hence, $\hat{\theta}$ in (e) above in this context is $\hat{\theta}'_{IFR_1} = log(\hat{\theta}_{IFR_1})$ and, similarly, $\hat{\theta}'_{IFR_2} = log(\hat{\theta}_{IFR_2})$.

Then, to estimate the nationwide pooled infection fatality rates (IFR_1 and IFR_2) for India, countrywide IFR estimates (pre-calculated or computed) among included studies (as verified through August 15, 2021) are pooled, as provided in (e) above using the random effects framework detailed. The nationwide pooled infection fatality estimate includes the computed IFRs from each of the four nationwide seroprevalence surveys conducted consecutively for India, as stratifying by time periods (i.e., the nationwide first and second waves of SARS-CoV-2 in India) is of particular interest.

To estimate the regional pooled infection fatality rates (IFR_1 and IFR_2) in India, IFR estimates (pre-calculated or computed) from included studies within a state are pooled, as provided in (e) above with the same random effects approach outlined. Then, the regional IFR is estimated as the pooled IFR across pooled state level IFRs, as provided in (e) except where i now denotes the i^{th} state. Since the regional analysis does not involve stratifying by waves (and thereby time points), for serial (or repeated) serosurveys for which multiple seroprevalence estimates are provided for a given study location at various time points, the most recent estimate is considered and included in the regional analysis.

Using the *meta* package in R, pooled effect sizes are estimated, as well as 95% confidence intervals, following the methodological framework above.

Appendix G. Summary of excluded articles from quantitative summary

Table 1. Summary of excluded articles from quantitative summary and reason for exclusion.

Reference	Location (Country–Location)	Reason for Exclusion
Kshatri, 2021a [4]	India–Bhubaneswar	No fatality data available
Kshatri, 2021b [5]	India–Bhubaneswar, Berhampur, Rourkela cities of Odisha	No fatality data available
Banaji, 2021 [7]	India–Chennai, Tamil Nadu	Provides no 95% confidence intervals
Bhattacharyya, 2021 [11]	India–Delhi	Provides no 95% confidence intervals
Other [8]	India–Delhi	Provides no 95% confidence intervals
Other [10]	India–Delhi	Provides no 95% confidence intervals
Hazra, 2021 [12]	India–Delhi, Mumbai, Pune, Bengaluru, Chennai	Provides no 95% confidence intervals
Misra, 2021 [13]	India–Delhi urban, Delhi rural, Bhubaneswar rural, Agartala rural, and Gorakhpur rural	No fatality data available
George, 2021 [14]	India–Devarajeevana Halli slum in Bengaluru, Karnataka	Provides seroprevalence in slum
Other [19]	India–Mumbai, Maharashtra	Provides no 95% confidence intervals
Other [21]	India–Mumbai, Maharashtra	Provides seroprevalence in slum and non-slum
Malani, 2020 [22]	India–Mumbai, Maharashtra	Provides seroprevalence in slum and non-slum
Bommer, 2020 [27]	India–nationwide	Provides no 95% confidence intervals
Bhaduri, 2020 [31]	India–nationwide, Delhi, Maharashtra	Provides no 95% confidence intervals
Banerjee, 2020 [32]	India–Pimpri-Chinchiwad, Maharashtra	No fatality data available
Goli, 2020 [33]	India–nationwide, Andhra Pradesh, Delhi, Gujarat, Haryana, Jammu & Kashmir, Karnataka, Kerala, Madhya Pradesh, Maharashtra, Rajasthan, Tamil Nadu, Telangana, Uttar Pradesh	Provides no 95% confidence intervals
Nisar, 2021 [37]	Pakistan–District East and District Malir in Karachi	Focuses on location outside of India
Haq, 2021 [38]	Pakistan–Khyber Pakhtunkhwa Sindh, Punjab	Focuses on location outside of India

Appendix H. Summary of seroprevalence estimates within India

Below is a forest plot with the seroprevalence estimates used to compute IFR_1 and in turn IFR_2 (except for studies for which IFR_2 was pre-calculated) in the meta-analysis of nationwide and regional IFRs.

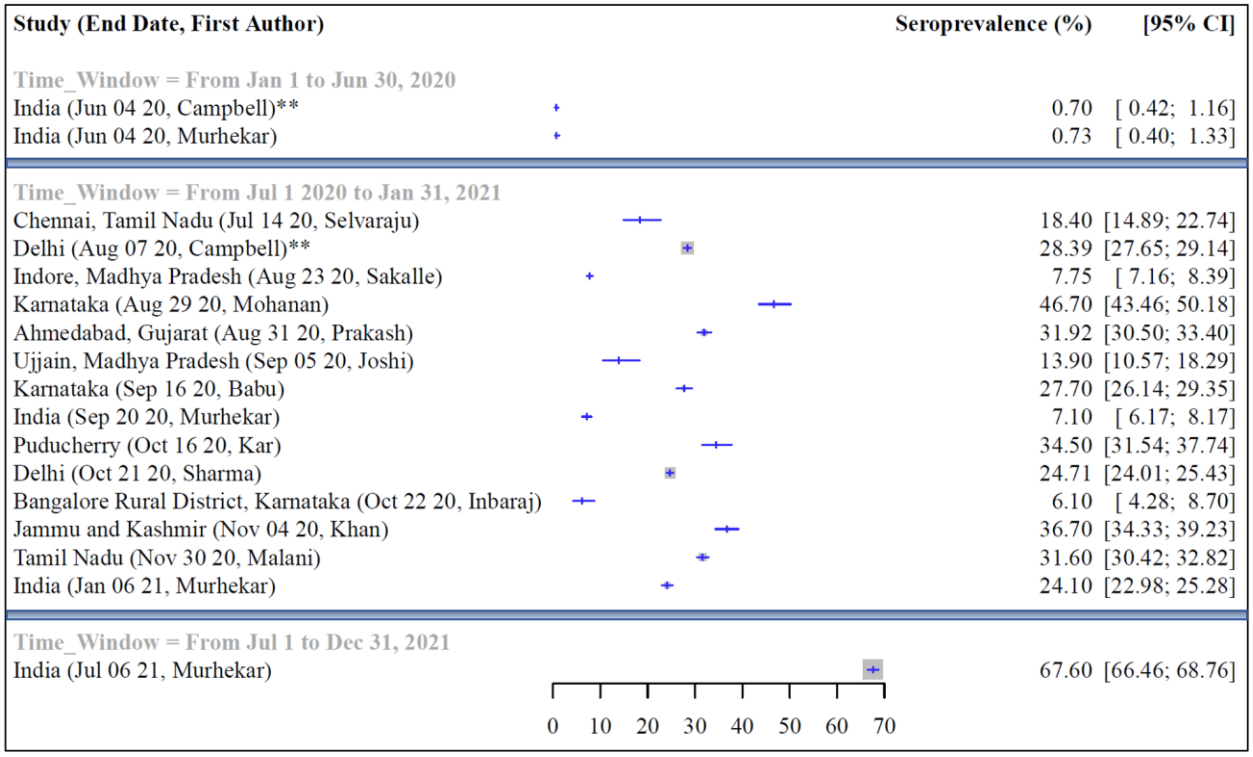


Figure 1. Forest plot of SARS-CoV-2 seroprevalence estimates for India utilized in meta-analysis of IFR_1 and IFR_2.

Appendix I. Risk of bias assessment across included articles

See supplementary file *Supplementary_RiskofBias.xlsx* for results from the risk of bias assessment among the included studies in the meta-analysis, using the Joanna Briggs Institute (JBI) tool. Responses to each question in the JBI approach, as well as the cumulative score and rank of risk of bias, are detailed for each of the 19 studies (i.e. 15 serosurvey studies and 4 other study designs).

Appendix J. Assessment of publication bias

To formally test for funnel plot asymmetry, the Egger's test (i.e., linear regression) is performed with a resulting p-value of 0.0501. Seeing as the significance level of the funnel plot intercept in the Egger's test nearly meets the benchmark of 0.05, we further conduct the Begg's test (i.e., rank correlation test) and with a p-value<0.0001, conclude that the funnel plot is asymmetric. As discussed within the ***Results*** section, despite the results of these diagnostic tests, we do not suspect that publication bias is the driving factor behind the observed asymmetry. Firstly, this is because the bulk of the included studies are seroprevalence studies, which are inherently large studies with rigorous study designs, thereby tending toward high precision (i.e., low standard errors). Secondly, there may be heterogeneity in the true effect size between the included studies for reasons such as geographic variation that may be attributing to the largely horizontal dispersion of the standard errors in ***Figure 6*** (the funnel plot) in the ***Results*** section, and funnel plots assume a single true effect size.

Appendix K. SEIR-fansy model framework

(Note: Explanation below is unchanged from Supplementary Materials in previous submission[1].)

Introduction

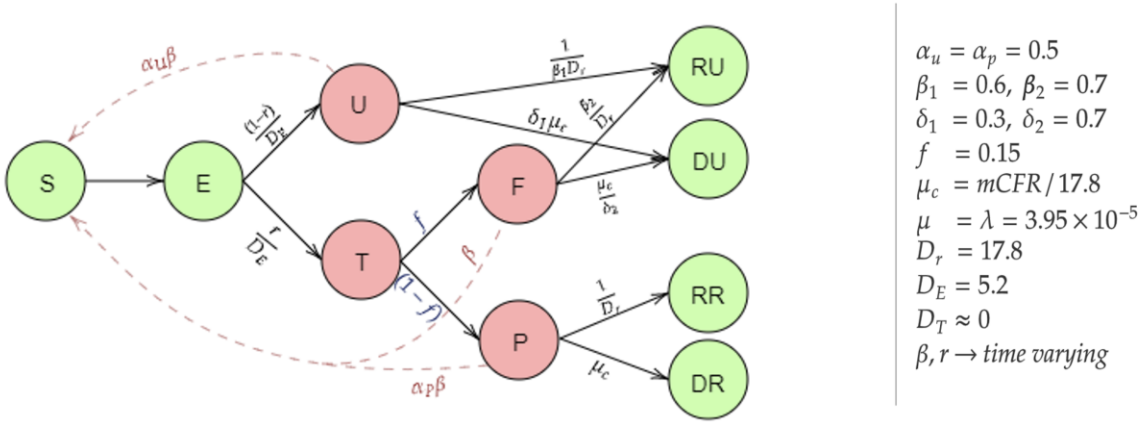
Here we are using the SEIR-fansy model[1,2] and software package[3] which uses a compartmental model accounting for false negative rates and preferential diagnostic testing for SARS-CoV-2 infections. The SEIR-fansy model can be represented by the compartmental model in Figure S1.

1. Purkayastha S, Kundu R, Bhaduri R, Barker D, Kleinsasser M, Debashree R, Mukherjee B. Estimating the wave 1 and wave 2 infection fatality rates from SARS-CoV-2 in India. *BMC Res Notes*. **14**, 262 (2021). doi:10.1186/s13104-021-05652-2.

2. Bhaduri R, Kundu R, Purkayastha S, Kleinsasser M, Beesley LJ, Mukherjee B. *Extending the Susceptible-Exposed-Infected-Removed (SEIR) model to handle the high false negative rate and symptom-based administration of Covid-19 diagnostic tests: SEIR-fansy.* medRxiv [Preprint]. 2020 Sep 25:2020.09.24.20200238. doi: 10.1101/2020.09.24.20200238. PMID: 32995829; PMCID: PMC7523173.

3. Ritwik Bhaduri, Ritoban Kundu, Soumik Purkayastha, Lauren Beesley and Bhramar Mukherjee (2020). *SEIRfansy: Extended Susceptible-Exposed-Infected-Recovery Model.* R package version 1.1.0. https://CRAN.R-project.org/package=SEIRfansy

Figure S1: Schematic diagram for the SEIR-fansy model with imperfect testing and misclassification.



Mathematical framework

The following differential equations summarize the transmission dynamics being modeled.

$$\frac{\partial S}{\partial t} = -\beta \frac{S(t)}{N}\left(\alpha_P P(t) + \alpha_U U(t) + F(t)\right) + \lambda N - \mu S(t)$$

$$\frac{\partial E}{\partial t} = \beta \frac{S(t)}{N}\left(\alpha_P P(t) + \alpha_U U(t) + F(t)\right) - \frac{E(t)}{D_e} - \mu E(t)$$

$$\frac{\partial U}{\partial t} = (1-r)\frac{E(t)}{D_e} - \frac{U(t)}{\beta_1 D_r} - \delta_1 \mu_c U(t) - \mu U(t)$$

$$\frac{\partial P}{\partial t} = (1-f)r\frac{E(t)}{D_e} - \frac{P(t)}{D_r} - \mu_c P(t) - \mu P(t)$$

$$\frac{\partial F}{\partial t} = fr\frac{E(t)}{D_e} - \frac{\beta_2 F(t)}{D_r} - \frac{\mu_c F(t)}{\delta_2} - \mu F(t)$$

$$\frac{\partial RU}{\partial t} = \frac{U(t)}{\beta_1 D_r} + \frac{\beta_2 F(t)}{D_r} - \mu RU(t)$$

$$\frac{\partial RR}{\partial t} = \frac{P(t)}{D_r} - \mu RR(t)$$

$$\frac{\partial DU}{\partial t} = \delta_1 \mu_c U(t) + \frac{\mu_c F(t)}{\delta_2},$$

$$\frac{\partial DR}{\partial t} = \mu_c P(t)$$

Using the Next Generation Matrix Method (28), we have calculated the basic reproduction number

$$R_0 = \frac{\beta S_0}{\mu D_e + 1}\left(\frac{\alpha_U(1-r)}{\frac{1}{\beta_1 D_r} + \delta_1 \mu_c + \mu} + \frac{\alpha_P r(1-f)}{\frac{1}{D_r} + \mu_c + \mu} + \frac{rf}{\frac{\beta_2}{D_r} + \frac{\mu_c}{\delta_2} + \mu}\right)$$

where $S_0 = \lambda/\mu = 1$ since we have assumed that natural birth and death rates are equal within this short period of time. In this setting, both β and r are time-varying parameters which are estimated using the Metropolis-Hastings MCMC method. To estimate the parameters, we at first need to solve the differential equations, which is difficult to perform in this continuous-time setting. It is also worth noting that we do not require the values of the variables for each time point. Instead, we only need their values at discrete time steps, i.e., for each day. Thus, we approximate the above set of differential equations by a set of recurrence relations. For any compartment X, the instantaneous rate of change with respect to time t (given by $\frac{\partial X}{\partial t}$) is approximated by the difference between the counts of that compartment on the $(t+1)^{th}$ day and the t^{th} day, that is $X(t+1) - X(t)$. Starting with an initial value for each of the compartments on the Day 1 and using the discrete-time recurrence relations, we can then

obtain the solutions of interest. Some examples of these discrete-time recurrence relations are presented below.

$$E(t+1) - E(t) = \beta \frac{S(t)}{N}\left(\alpha_P P(t) + \alpha_U U(t) + F(t)\right) - \frac{E(t)}{D_e} - \mu E(t),$$
$$U(t+1) - U(t) = \frac{(1-r)E(t)}{D_e} - \frac{U(t)}{\beta_1 D_r} - \delta_1 \mu_c\, U(t) - \mu U(t),$$
$$P(t+1) - P(t) = \frac{r(1-f)E(t)}{D_e} - \frac{P(t)}{D_r} - \mu_c P(t) - \mu P(t),$$
$$F(t+1) - F(t) = \frac{rfE(t)}{D_e} - \frac{\beta_2 F(t)}{D_r} - \frac{\mu_c\, F(t)}{\delta_2} - \mu F(t).$$

The rest of the differential equations can each be similarly approximated by a discrete-time recurrence relation.

Likelihood assumptions and estimation

We use Bayesian estimation techniques and Markov chain Monte Carlo (MCMC) methods (namely, Metropolis-Hastings method with Gaussian proposal distribution) for estimating the parameters. First, we approximated the above set of differential equations using a discrete time approximation using daily differences. So, after we started with an initial value for each of the compartments on the day 1, using the discrete time recurrence relations we can find the counts for each of the compartments on the next days. To proceed with the MCMC-based estimation, we specify the likelihood explicitly. We assume (conditional on the parameters) the number of new confirmed cases on day t depend only on the number of exposed individuals on the previous day. Specifically, we use multinomial modeling to incorporate the data on recovered and deceased cases as well. The joint conditional distribution is

$$P[P_{new}(t), R_{new}(t), D_{new}(t) | E(t-1), P(t-1)]$$
$$= P[P_{new}(t) | E(t-1), P(t-1)].\, P[\, R_{new}(t), D_{new}(t) | E(t-1), P(t-1)]$$
$$= P[P_{new}(t) | E(t-1)].\, P[\, R_{new}(t), D_{new}(t) | P(t-1)]$$

A multinomial distribution-like structure is then defined,

$$P_{new}(t) | E(t-1) \;\sim\; Bin\left(E(t-1), \frac{r(1-f)}{D_e}\right)$$

$$R_{new}(t), D_{new}(t) | P(t-1) \;\sim\; Mult\left(P(t-1), \left(\frac{1}{D_r}, \mu_c, 1 - \frac{1}{D_r} - \mu_c\right)\right)$$

Note: the expected values of $E(t-1)$ and $P(t-1)$ are obtained by solving the discrete time differential equations as described earlier.

Prior assumptions and MCMC

For the parameter r, we assume a $U(0,1)$ prior, while for β, we assume an improper non-informative flat prior with the set of positive real numbers as support. After specifying the likelihood and the prior distributions of the parameters, we draw samples from the posterior distribution of the parameters using the Metropolis-Hastings algorithm with a Gaussian proposal distribution. We run the algorithm for 200,000 iterations with a burn-in period of 100,000. Finally, the mean of the parameters in each of the iterations are obtained as the final estimates of β and r for the different time periods. To obtain confidence intervals of various estimates we predict the number of individuals in each compartment given a set of parameters which are drawn using MCMC. This is done for 100,000 iterations. Using these values, we obtain the 95% Bayesian Credible Intervals of the estimates (such as infection fatality rates and underreporting factors)

Estimation of parameters of interest

Our main parameters of interest here are Underreporting factors for cases and deaths and Infection Fatality rate. Underreporting factors (URF) for cases and deaths are defined as follows:

$$URF_{case} = \frac{Estimated\ Total\ Cumulative\ Infections}{Observed\ Cumulative\ Cases}$$

$$URF_{death} = \frac{Estimated\ Total\ Cumulative\ \ Deaths}{Observed\ Cumulative\ Deaths}$$

Here, total cumulative cases refers to all Cumulative cases including both reported and unreported cases. Similarly total cumulative deaths includes both reported and unreported deaths. Since we are unable to observe unreported cases or deaths we estimate total cumulative cases and deaths as follows:

1. Total Cumulative cases at time *t* = *P(t)+U(t)+F(t)+RR(t)+RU(t)+DR(t)+DU(t)*
2. Total Cumulative deaths at time *t* = *DR(t)+DU(t)*

To estimate the true fatality rate of COVID-19, we calculate 2 different infection fatality rates IFR1 and IFR2 as defined in formulas (a) and (b) respectively, in ***Supplementary Appendix F***.

We also calculate the Case fatality rate as defined in the ***Methods*** section.

Now $Cumulative\ Deaths$ follows a $Bin(Observed\ cumulative\ cases, CFR_{true})$ distribution, with the estimate of CFR_{true} given by CFR, making CFR is a binomial proportion . Let $\hat{p} = CFR$ and $n = Observed\ Cumulative\ Cases$. So the asymptotic approximate 95% confidence interval is given by

$$(\hat{p} - 1.96\sqrt{\frac{\hat{p}(1-\hat{p})}{n}}, \hat{p} + 1.96\sqrt{\frac{\hat{p}(1-\hat{p})}{n}}).$$

The estimates of infection fatality rates and underreporting factors are based on Bayesian credible intervals constructed from the exact posterior draws, as described before.

Appendix L. Data source and model-based results

The data has been sourced from *covid19india.org*. We used daily case-recovery-death count data from April 1, 2020 to January 31, 2021 for wave 1 and from February 1, 2021 – June 30, 2021 for wave 2. The predicted number of reported and total cases and deaths for January 31, 2021 (wave 1) and June 30 (for wave 2 and waves 1 and 2 combined) are shown in Tables S1, S2, and S3 respectively.

The mean estimates and the 95% CrI's of underreporting factors for cases and deaths on January 31, 2021 are shown in ***Figure S2.*** Relevant wave 2 values are presented in ***Figure S3.***

Table T1: Summary of the different metrics for the states and the nation for wave 1, on 31st January 2021

Place	Reported Cases (Observed)	Reported Cases (Predicted)	Total (reported + unreported) Cases (Predicted)	Reported Deaths (Observed)	Reported Deaths (Predicted)	Total (reported + unreported) Deaths (Predicted)	Cases per million	Deaths per million
Andaman and Nicobar	4990	4971	420209	62	62	1027	13111.53	162.91
Andhra Pradesh	887836	882030	38244770	7153	7125	64317	17908.19	144.28
Arunachal Pradesh	16828	16367	1177129	56	54	773	12161.36	40.47
Assam	217039	206824	1576369	1087	1050	2650	6955.14	34.83
Bihar	260719	265325	1752581	1501	1515	3566	2504.52	14.42
Chandigarh	20925	21064	370319	334	330	1456	19825.67	316.45
Chhattisgarh	305367	306365	3958345	3701	3573	12372	11953.99	144.88
Dadra and Nagar Haveli	3377	3353	322500	2	2	38	5765.12	3.41
Delhi	635096	634237	17949712	10853	10771	68212	37830.49	646.48
Goa	53409	53536	1516370	768	763	4854	36618	526.55
Gujarat	261539	239728	1546257	4386	3937	9160	4327.27	72.57
Haryana	267897	255093	2212182	3018	2849	7763	10567.32	119.05
Jammu and Kashmir	124506	120675	11786372	1936	1861	35906	10149.64	157.82
Jharkhand	118667	108448	1142000	1072	973	2982	3597.26	32.5
Karnataka	939387	931828	7298441	12224	12112	31189	15375.77	200.08
Kerala	929179	973432	6109388	3744	3821	8781	27814.68	112.08
Ladakh	9720	9875	195168	130	131	627	35474.45	474.45
Madhya Pradesh	255112	246254	2593075	3811	3617	11092	3512.64	52.47
Maharashtra	2026399	1939901	11106302	51081	48974	107479	18032.58	454.56
Manipur	29068	28426	787087	371	359	2239	11308.79	144.34
Meghalaya	13716	12742	496017	146	135	1126	4623.02	49.21
Mizoram	4372	4488	237273	9	9	98	3984.67	8.2
Nagaland	12057	11586	315789	82	83	506	6094	41.45
Odisha	335072	322600	1630327	1959	1882	3873	7982.8	46.67
Punjab	173276	176267	1553488	5615	5670	15692	6245.68	202.39
Rajasthan	317491	295702	1696333	2766	2552	5569	4631.63	40.35
Sikkim	6104	6136	177128	133	135	877	9997.1	217.83
Tamil Nadu	838340	842658	5966633	12356	12378	30119	11619.88	171.26
Telangana	293959	287679	1625763	1599	1560	3426	8397.95	45.68
Tripura	33347	32051	801142	388	374	2131	9076.69	105.61
Uttar Pradesh	600299	584173	3838576	8658	8418	19731	3004.31	43.33
Uttarakhand	96129	94366	2147503	1644	1609	8655	9530.66	162.99
West Bengal	569998	548980	3171287	10173	9735	21392	6244.77	111.45
India	10758629	10512888	119510413	154428	149478	550380	8022.84	115.16

Table T2: Summary of the different metrics for the states and the nation for wave 2, on 30th June 2021

Place	Reported Cases (Observed)	Reported Cases (Predicted)	Total (reported + unreported) Cases (Predicted)	Reported Deaths (Observed)	Reported Deaths (Predicted)	Total (reported + unreported) Deaths (Predicted)	Cases per million	Deaths per million
Andaman and Nicobar	2475	2538	22006	66	63	178	6503.21	173.42
Andhra Pradesh	1005454	1052130	24433883	5590	5404	30424	20280.61	112.75
Arunachal Pradesh	19341	21105	168634	120	115	308	13977.47	86.72
Assam	293999	320108	10416260	3494	3439	25964	9421.36	111.97
Bihar	461307	459699	9984295	8089	7695	40041	4431.41	77.7
Chandigarh	40730	41573	581721	474	468	1746	38590.17	449.1
Chhattisgarh	689201	703661	12440190	9739	9717	42812	26979.67	381.25
Dadra and Nagar Haveli	7047	7415	132289	2	2	9	12030.44	3.41
Delhi	799064	806934	14348458	14125	14016	62005	47597.5	841.38
Goa	113451	116695	1343287	2292	2244	7401	77783.68	1571.43
Gujarat	561769	593952	9133281	5674	5834	23185	9294.7	93.88
Haryana	500735	522462	10517838	6424	6479	31671	19751.72	253.4
Jammu and Kashmir	191410	197500	7943113	2391	2315	20502	15603.61	194.91
Jharkhand	226971	236331	4274772	4040	4079	18394	6880.38	122.47
Karnataka	1907238	1962929	37788085	22914	22533	107790	31217.43	375.05
Kerala	2004396	2083298	23997385	9599	9266	30606	60000.97	287.34
Ladakh	10366	10916	117421	72	72	224	37832.12	262.77
Madhya Pradesh	534581	549186	8512735	5169	5160	20615	7360.66	71.17
Maharashtra	4042252	4073053	59223522	71088	70007	268306	35971.31	632.6
Manipur	41220	46295	481010	791	772	2480	16036.48	307.74
Meghalaya	36326	38828	1512205	698	674	6122	12243.8	235.26
Mizoram	16120	17044	306787	84	86	427	14691.86	76.56
Nagaland	13206	13915	383920	410	423	2782	6674.75	207.23
Odisha	577736	594332	20182943	2157	1989	15246	13764.07	51.39
Punjab	422429	421946	10421537	10456	9990	57838	15226.32	376.88
Rajasthan	634910	633034	16637039	6157	5919	35662	9262.21	89.82
Sikkim	14575	15696	218046	175	182	703	23870.86	286.61
Tamil Nadu	1645335	1726816	40903538	20358	19214	109652	22805.3	282.17
Telangana	329792	333956	8438699	2068	2005	11775	9421.64	59.08
Tripura	32869	35134	1214075	291	271	2236	8946.58	79.21
Uttar Pradesh	1105782	1132551	25351545	13939	13930	69963	5534.1	69.76
Uttarakhand	244199	253662	4885358	5676	5771	27475	24210.98	562.74
West Bengal	931107	958952	24747185	7556	7329	43904	10200.99	82.78
India	19690200	19890297	2.61E+08	245824	236813	850612	14683.22	183.31

Table T3: Summary of the different metrics for the states and the nation for waves 1 and 2 combined, on 30th June 2021

Place	Reported Cases (Observed)	Reported Cases (Predicted)	Total (reported + unreported) Cases (Predicted)	Reported Deaths (Observed)	Reported Deaths (Predicted)	Total (reported + unreported) Deaths (Predicted)	Cases per million	Deaths per million
Andaman and Nicobar	6589	7509	442215	88	125	1205	19614.74	336.33
Andhra Pradesh	1435447	1934160	62678653	9372	12529	94741	38188.8	257.03
Arunachal Pradesh	21803	37472	1345763	81	169	1081	26138.83	127.19
Assam	328526	526932	11992629	2184	4489	28614	16376.5	146.8
Bihar	651888	725024	11736876	3831	9210	43607	6935.93	92.12
Chandigarh	55352	62637	952040	635	798	3202	58415.84	765.55
Chhattisgarh	912468	1010026	16398535	11734	13290	55184	38933.66	526.13
Dadra and Nagar Haveli	9515	10768	454789	4	4	47	17795.56	6.82
Delhi	1393747	1441171	32298170	21504	24787	130217	85427.99	1487.86
Goa	135851	170231	2859657	2099	3007	12255	114401.7	2097.98
Gujarat	752544	833680	10679538	9114	9771	32345	13621.97	166.45
Haryana	694384	777555	12730020	6685	9328	39434	30319.04	372.45
Jammu and Kashmir	244553	318175	19729485	3147	4176	56408	25753.25	352.73
Jharkhand	315475	344779	5416772	4479	5052	21376	10477.64	154.97
Karnataka	2203361	2894757	45086526	21841	34645	138979	46593.2	575.13
Kerala	2147727	3056730	30106773	6427	13087	39387	87815.65	399.42
Ladakh	16439	20791	312589	165	203	851	73306.57	737.22
Madhya Pradesh	731319	795440	11105810	6988	8777	31707	10873.3	123.64
Maharashtra	5378150	6012954	70329824	81475	118981	375785	54003.89	1087.16
Manipur	39722	74721	1268097	578	1131	4719	27345.27	452.08
Meghalaya	23284	51570	2008222	320	809	7248	16866.82	284.47
Mizoram	8678	21532	544060	24	95	525	18676.53	84.76
Nagaland	18039	25501	699709	203	506	3288	12768.75	248.68
Odisha	612220	916932	21813270	2366	3871	19119	21746.87	98.06
Punjab	497663	598213	11975025	11891	15660	73530	21472	579.27
Rajasthan	859576	928736	18333372	6777	8471	41231	13893.84	130.17
Sikkim	11424	21832	395174	205	317	1580	33867.96	504.44
Tamil Nadu	1598092	2569474	46870171	17669	31592	139771	34425.18	453.43
Telangana	528216	621635	10064462	2949	3565	15201	17819.59	104.76
Tripura	40813	67185	2015217	428	645	4367	18023.27	184.82
Uttar Pradesh	1619541	1716724	29190121	17546	22348	89694	8538.41	113.09
Uttarakhand	287279	348028	7032861	4811	7380	36130	33741.64	725.73
West Bengal	1133393	1507932	27918472	13281	17064	65296	16445.76	194.23
India	24963227	30403185	3.81E+08	273779	386291	1400992	22706.06	298.47

Table T4: Parameter values and descriptions for the SEIR-fansy model.

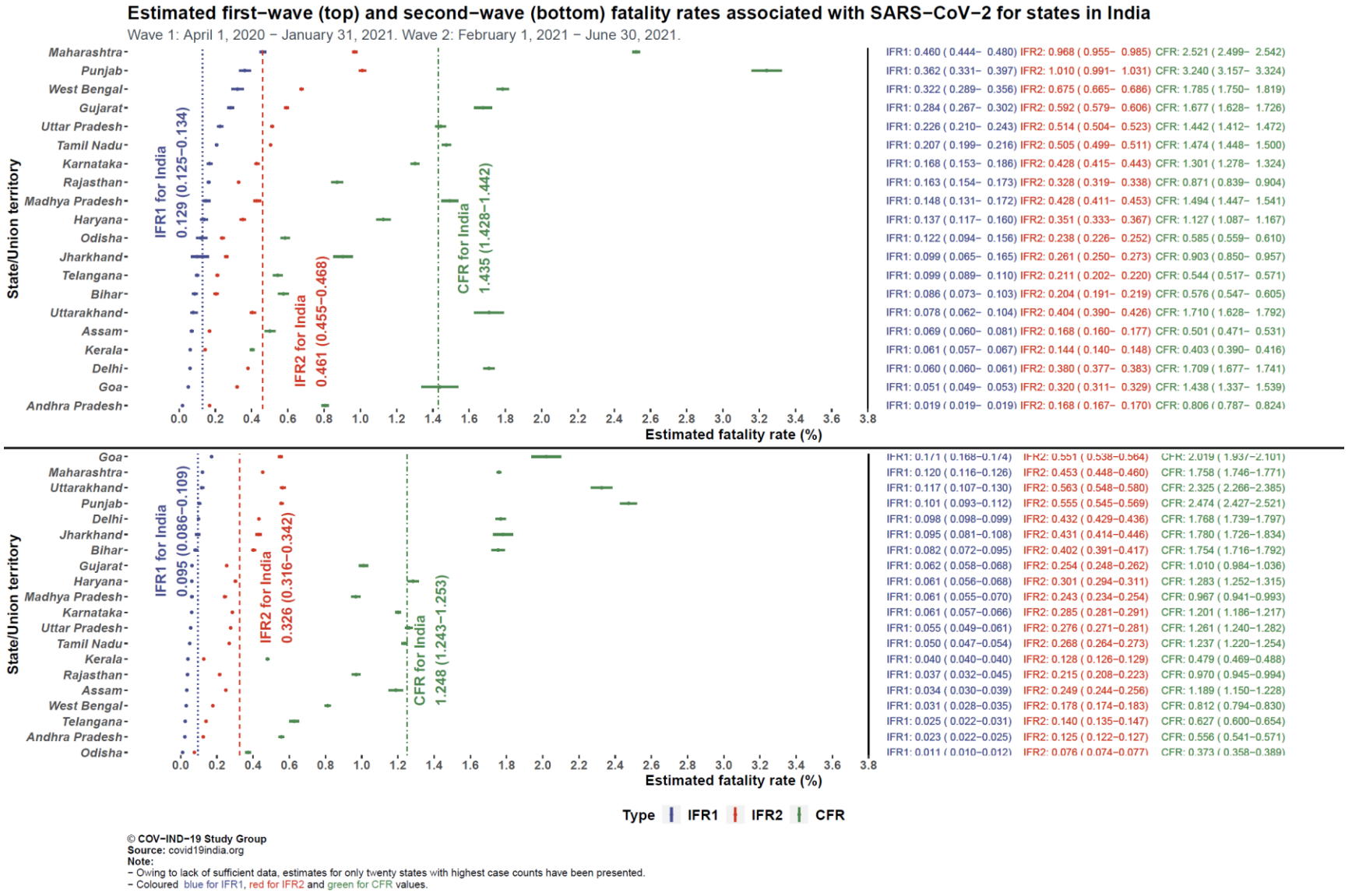
Parameter	Value	Description
	Time-varying	Rate of infectious transmission by infected, tested individuals with false negative results.
p	0.5	Ratio of rate of spread of infection by tested positive patients to that by false negatives. p < 1 represents the scenario where individuals who test positive are infecting susceptible individuals are a lower rate than infected individuals with false negative test results.
u	0.5	Scaling factor for the rate of spread of infection by untested individuals. u is assumed to be < 1 as U mostly consists of asymptomatic or mildly symptomatic cases who are known to spread the disease at a much lower rate than those with higher levels of symptoms.
De	5.2	Incubation period (in days).
Dr	17.8	Means number of days until recovery for infected individuals.
Dt	0	Mean number of days for the test result to come after a person is tested. Under the assumption of instantaneous test results, this is taken to be zero.
c	0.0562	Death rate attributable to COVID-19 which is equivalent to inverse of the average number of days for death starting from the onset of disease times the probability of death of an infected individual.
λ, μ	3.95×10^{-5}	Natural birth and death rates (assumed to be equal).
r	*Time-varying*	Probability of being tested for infectious individuals.
f	0.15	Probability of a false negative RT-PCR diagnostic test result.
1, 12	0.6 (1) 0.7 (2)	Scaling factors for rate of recovery for undetected and false negative individuals respectively. Both 1 and 2 are assumed to be less than 1. It is assumed that the recovery rate is slower than the detected ones for the False Negative ones because they are not getting any hospital treatments. The condition of Untested individuals is not so severe as they consist of mostly asymptomatic people. So, they are assumed to recover faster than the Current Positive Ones.
1, 12	0.3 (1) 0.7 (2)	Scaling factors for death rate for undetected and false negative individuals respectively. Both 1 and 2 are assumed to be less than 1. Same as before, the death rate for False Negative ones are assumed to be higher than the Current detected Positive as they are not receiving proper treatment. While, for the Untested ones, the death rate is taken to be lesser because they are mostly asymptomatic. So, their probability of dying is much less.

Table T5: Comparison of 4th nationwide serosurvey to combined estimates across waves 1 and 2.

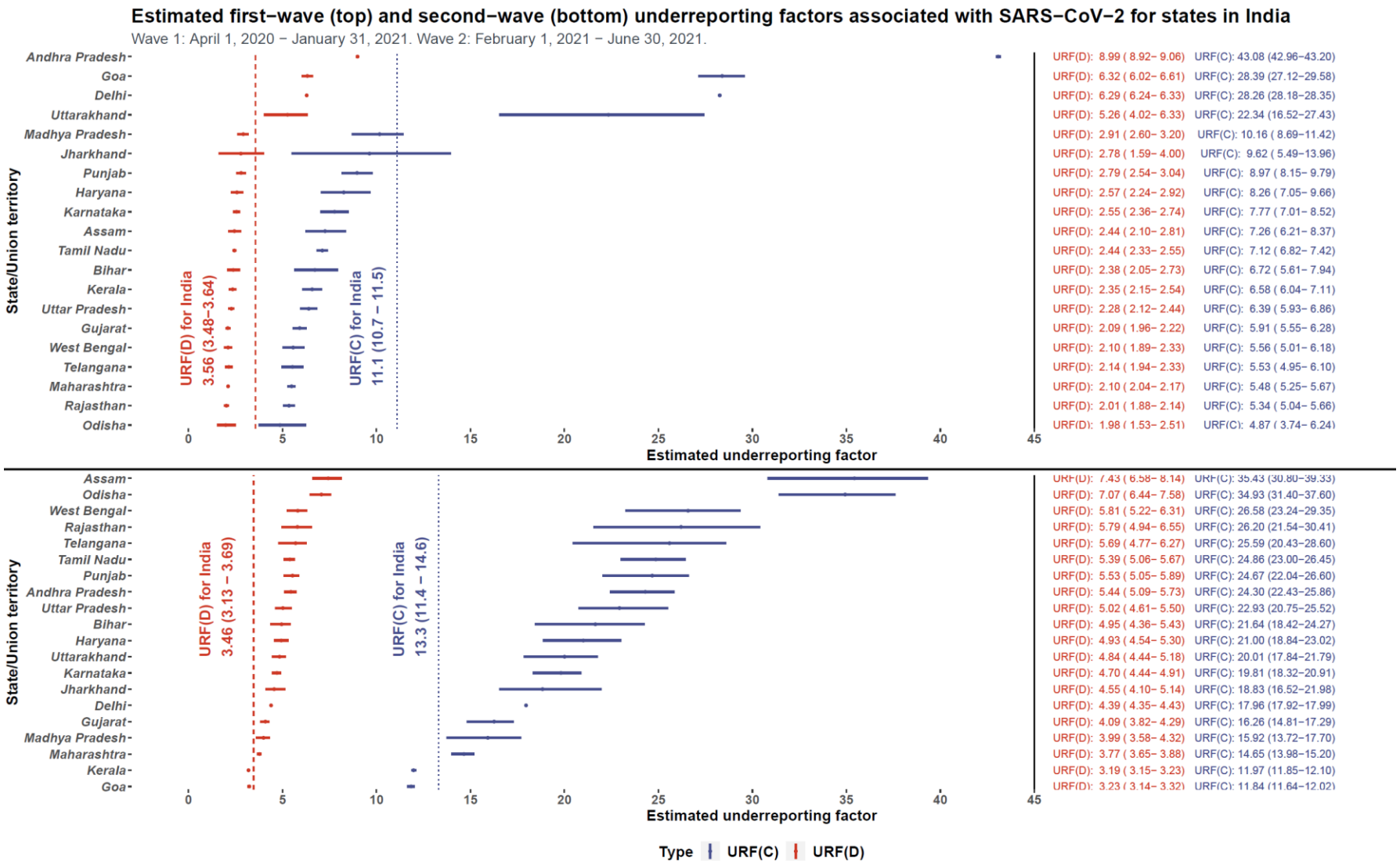
	4th Nationwide Serosurvey, 31 May 2021[1]				Model-Based Estimates, 30 June 2021			
States	Seroprevalence (%)	Estimated Cases (in Lakhs)	Reported Cases (in Lakhs)	Under Counting Factor	Estimated Cases	Reported Cases	Under Reporting Factor	Difference (Under Counting factor - Under Reporting factor)
Bihar	75.9	947	7	134	11733035	725024	16	118
Uttar Pradesh	71	1689	17	100	29700720	1716724	17	83
Madhya Pradesh	79	674	8	86	11248345	795440	14	72
Jharkhand	61.2	236	3	70	5494715	344779	16	54
Rajasthan	76.2	617	9	66	18167796	928736	20	46
Gujarat	75.3	481	8	59	11073822	833680	13	46
West Bengal	60.9	607	14	44	28541606	1507932	19	25
Assam	50.3	179	4	44	12843468	526932	24	20
Telangana	63.1	243	6	42	10136279	621635	16	26
Odisha	68.1	316	8	41	22332360	916932	24	17
Punjab	66.5	200	6	35	11989926	598213	20	15
Jammu & Kashmir	63	86	3	30	19619546	318175	62	-32
Tamil Nadu	69.2	539	21	26	48926546	2569474	19	7
Uttarakhand	73.1	82	3	25	7182789	348028	21	4
Himachal Pradesh	62	46	2	24	*N/A*	*N/A*	*N/A*	*N/A*
Chhattisgarh	74.6	220	10	23	459405	10768	43	-20
Haryana	60.1	169	8	22	13080661	777555	17	5
Andhra Pradesh	70.2	378	17	22	63562840	1934160	33	-11
Karnataka	69.8	472	26	18	46131203	2894757	16	2
Maharashtra	58	714	57	12	70307014	6012954	12	0
Kerala	44.4	159	25	6	31342383	3056730	10	-4
India	67.6	9265	282	33	380801295	30403185	13	20

N/A = Not available.

[1] Press Information Bureau, National Media Center. Briefing on COVID-19. July 20, 2021.



Supplementary Figure 2. Forest plot of wave 1 and wave 2 infection fatality rates (IFR) and case fatality ratios (CFR) for SARS-CoV-2 in various states in India, where IFR_1 includes reported deaths and IFR_2 further includes the estimate of unreported deaths.



Supplementary Figure 3: Estimated first and second wave underreporting factors for cases and deaths associated with SARS-CoV-2 for states in India.

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